Solar Hydrogen Production

6th International Conference on Hydrogen Production

Oshawa, May 5th, 2015

Dr. Christian Sattler

Christian.sattler@dlr.de

Introduction

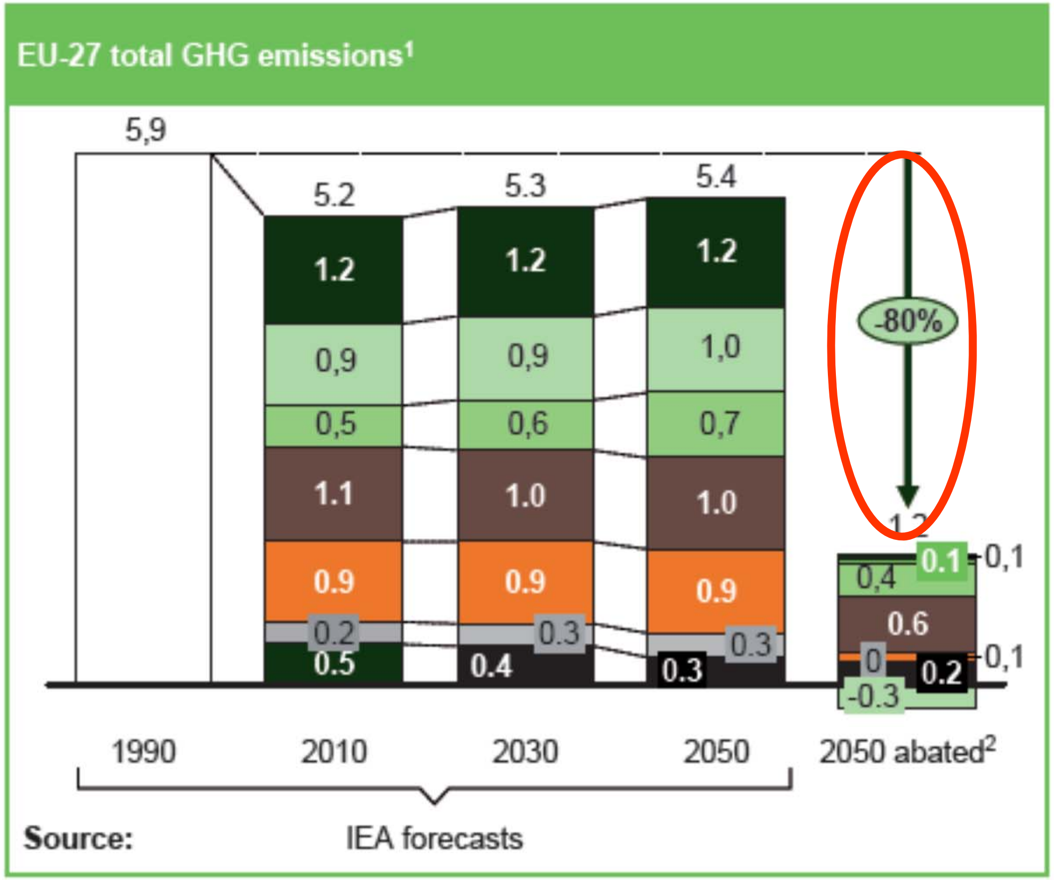
- Motivation: Political, Economical, Ecological, Technical
- Concentrating Solar Systems
- Solar fuels technology developments and demonstrations
- R&D needs and networks

Political Driver: Example – EU Sustainable Energy Technology Plan (SET-Plan 2007)

- **Goals of the EU until 2020 (20/20/20)**
  - **20%** higher energy efficiency
  - **20%** less GHG emission
  - **20%** renewable energy
- **Goal of the EU until 2050:**
  - **80%** less CO_2 emissions than in 1990

- Significant research effort for the development of a new generation of CO_2 emission free energy technologies, like
  - Offshore-Wind
  - **Solar**
  - 2^{nd} generation Biomass

Development of EU GHG emissions [Gt CO_2e]

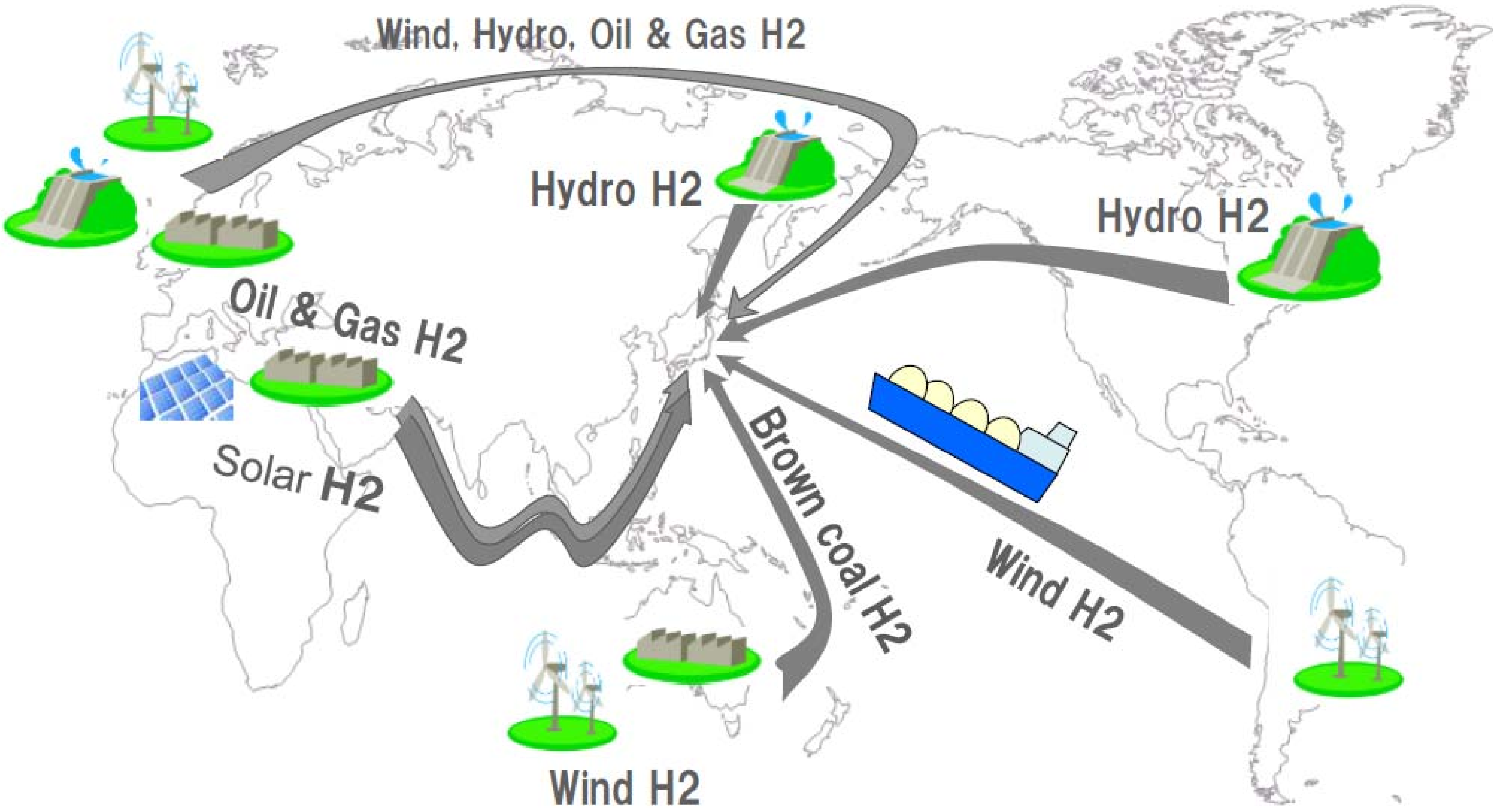


Sector	Total abatement
Power	95-100%
Road transport	95%
Air & sea transport	50%
Industry[3]	40%
Buildings	95%
Waste	100%
Agriculture	20%
Forestry	-0.25 Gt CO_2e

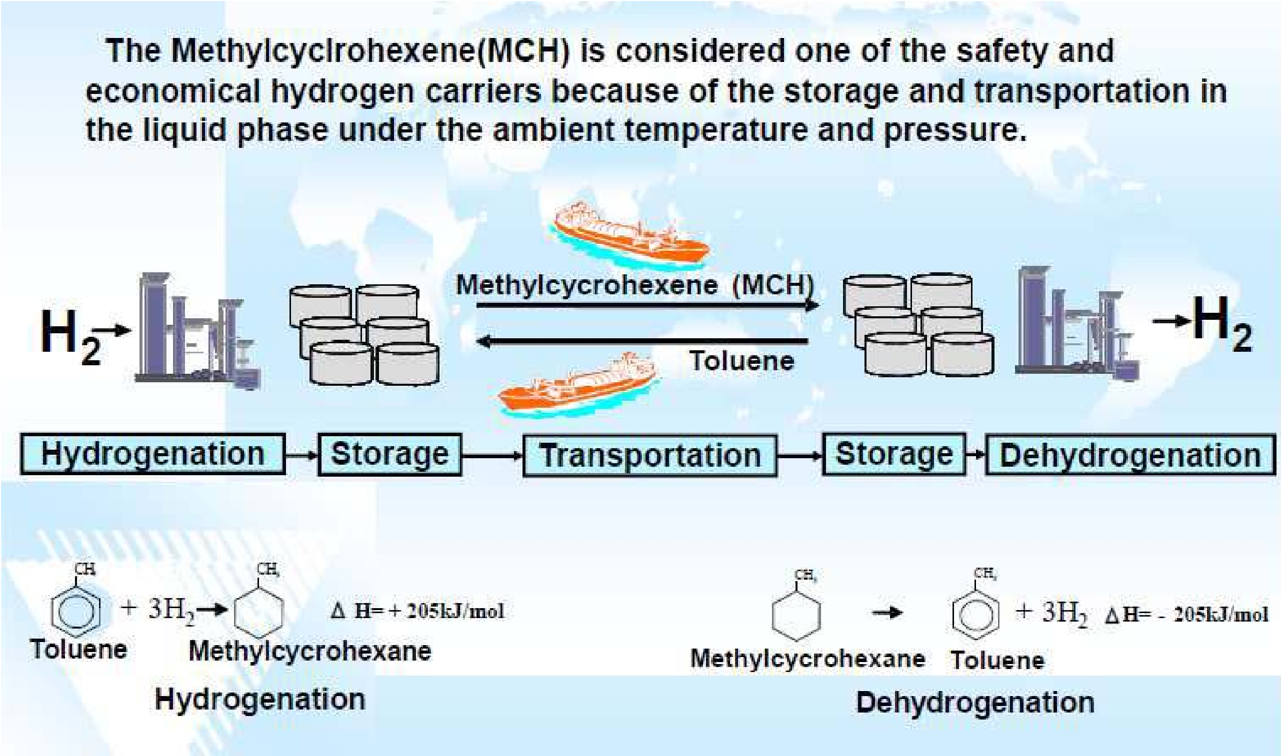
1 Large efficiency improvements are already included in the baseline based on the International Energy Agency, World Energy Outlook 2009, especially for industry
2 Abatement estimates within sector based on Global GHG Cost Curve
3 CCS applied to 50% of large industry (cement, chemistry, iron and steel, petroleum and gas, not applied to other industries)

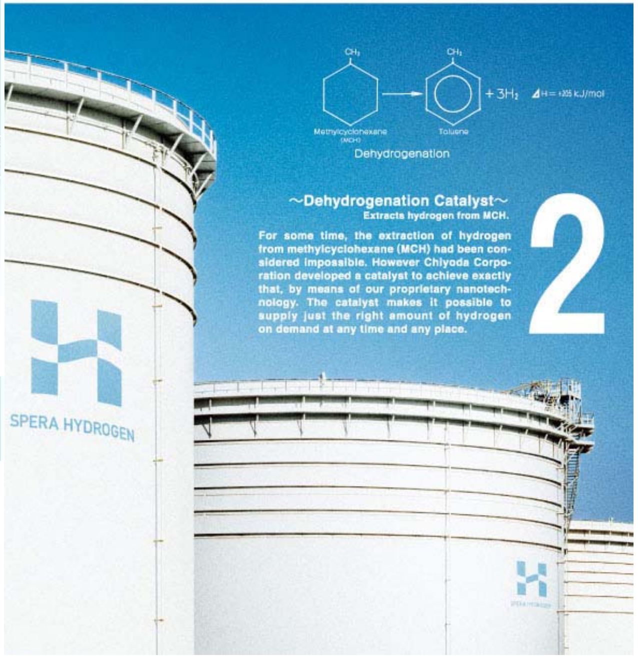
SOURCE: www.roadmap2050.eu

Kawasaki Vision – Hydrogen Potential from Overseas

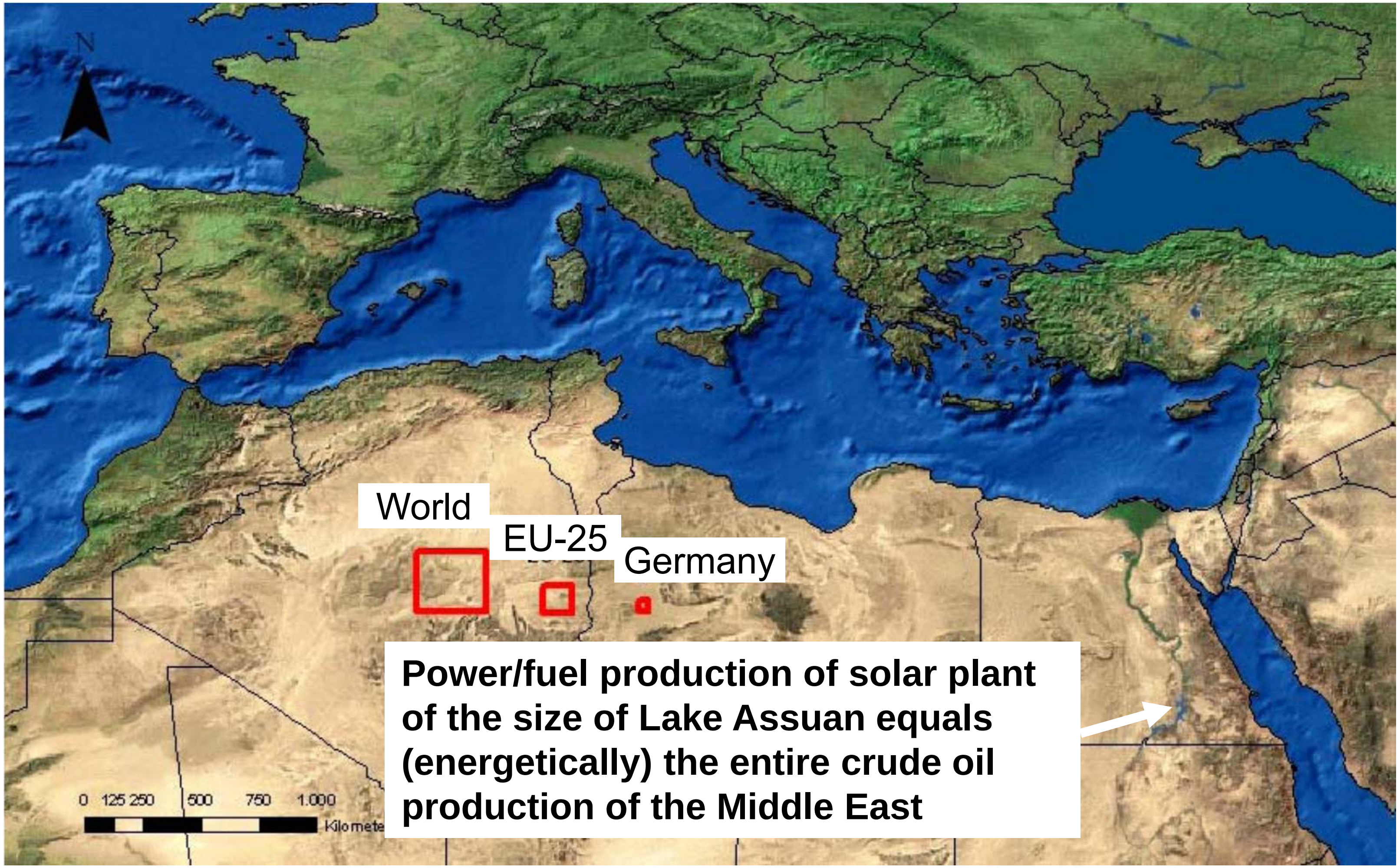


CHIYODA – Hydrogen Vision



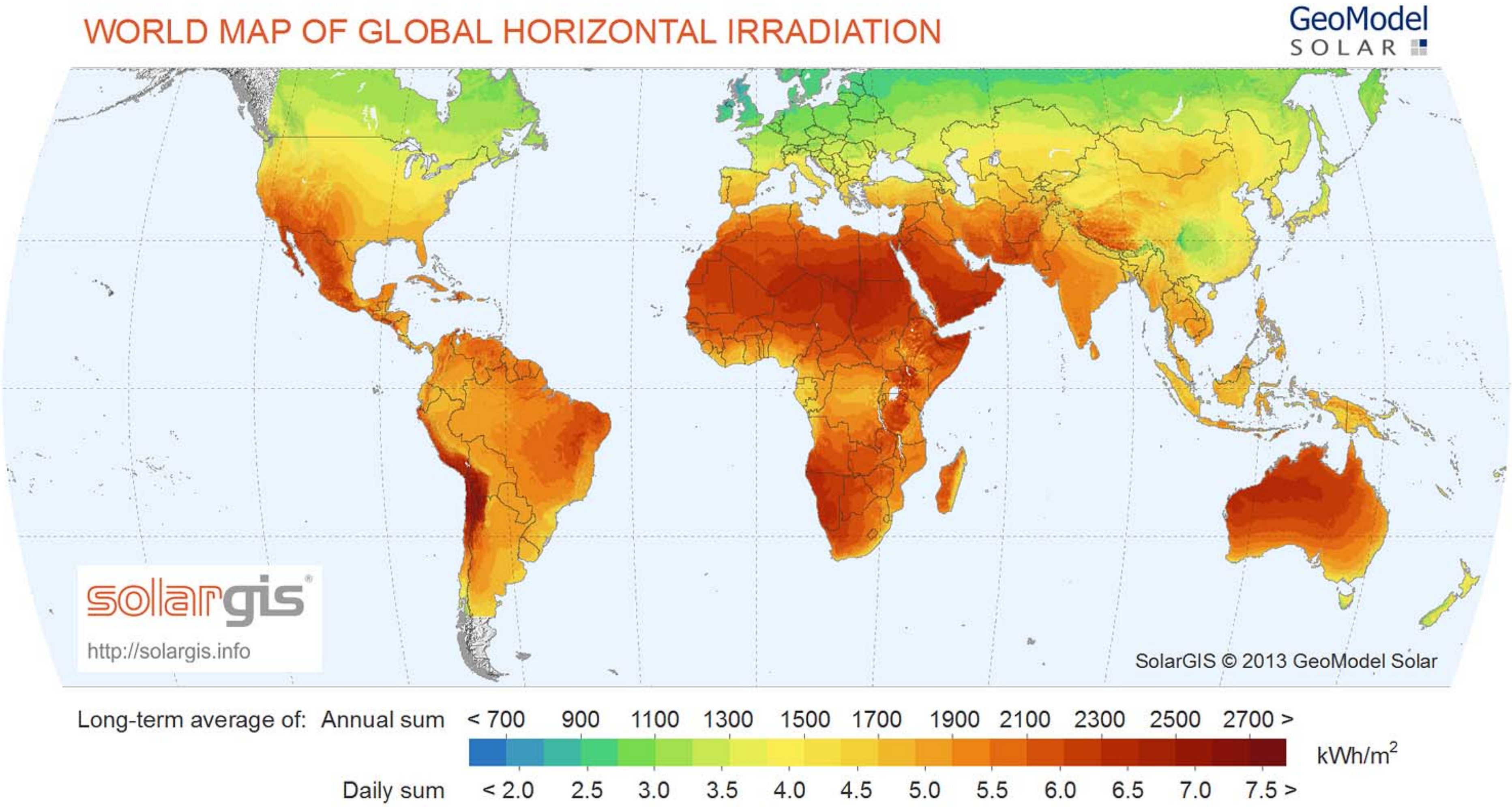


Potential of Solar Energy



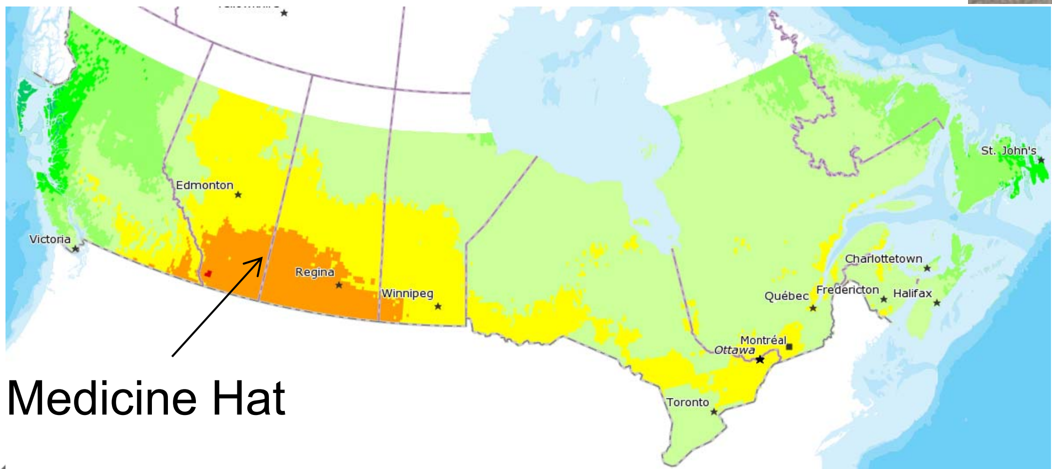
DLR

Potential of Solar Energy



CSP in Canada
1 MW_e Demonstration Plant
Medicine Hat, Alberta

- Integrated Solar Combined Cycle demonstration with a capacity of 1 MW_e
- Connected to the 203 MW_e municipal power plant
- Location: 50.04° N; 110.72° W
- Average annual DNI 1833 kWh/m^2
- Annual output 4100 MWh_{th}



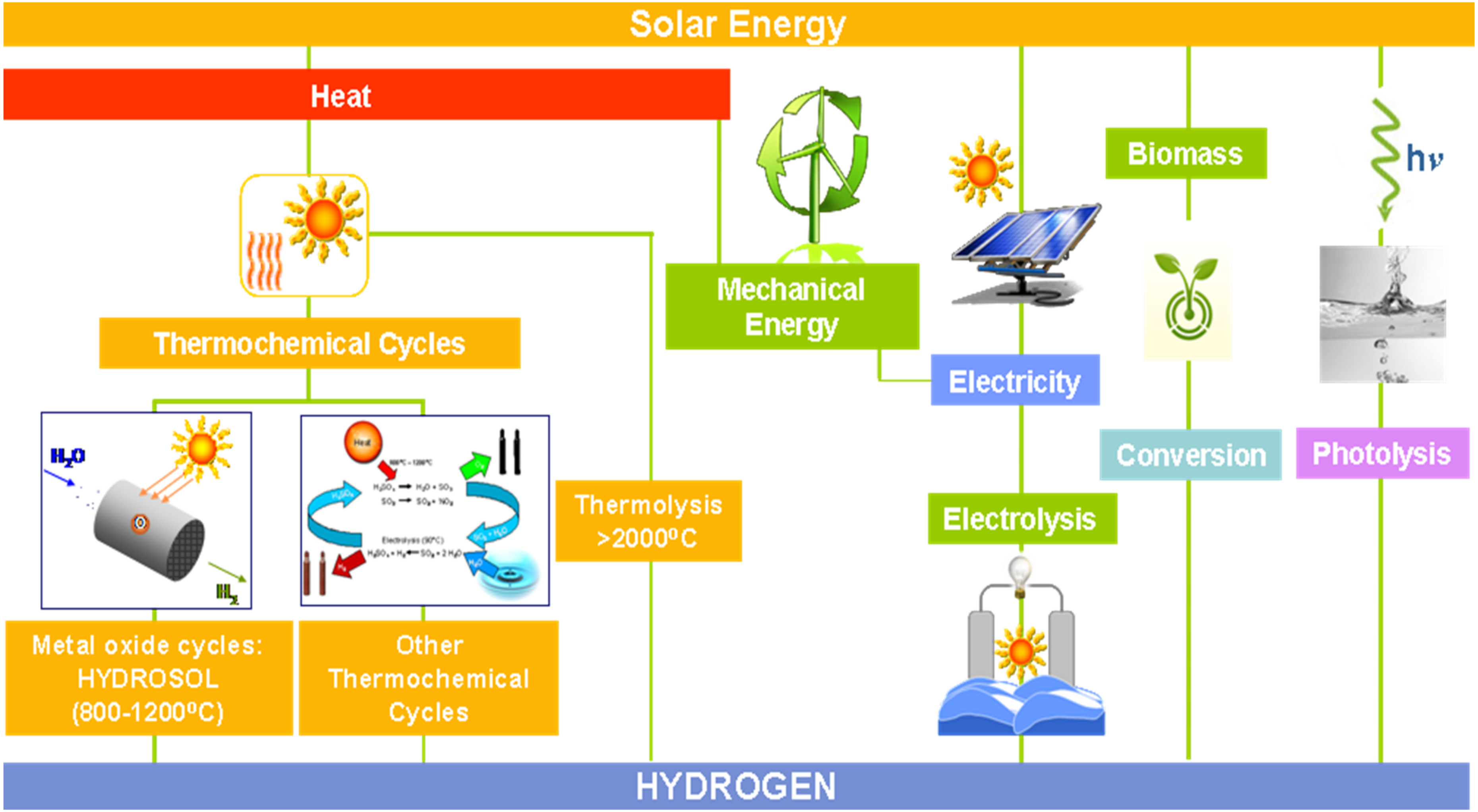
DNI annual average

- 700 - 900
- 901 - 1100
- 1101 - 1300
- 1301 - 1500
- 1501 - 1700
- 1701 - 1900
- > 1900

Source: NRCAN/CANMET

DLR

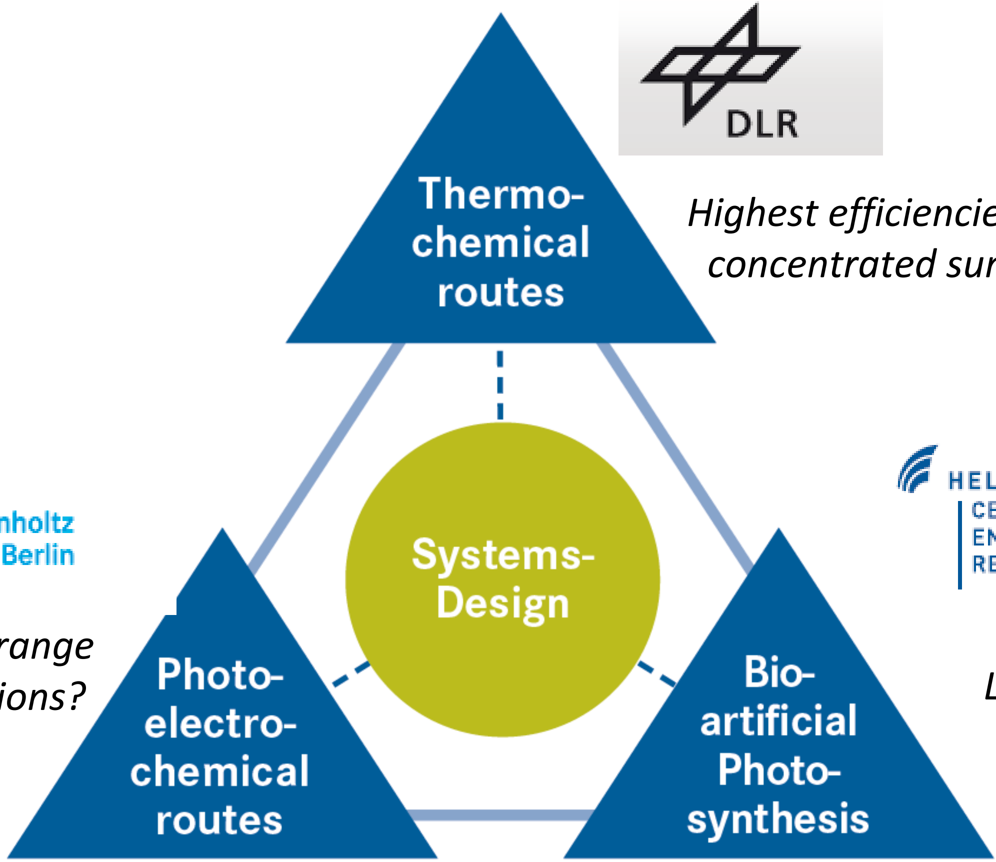
Solar Hydrogen



German Strategy and Approach on Solar Fuels

Goal in the Helmholtz Association

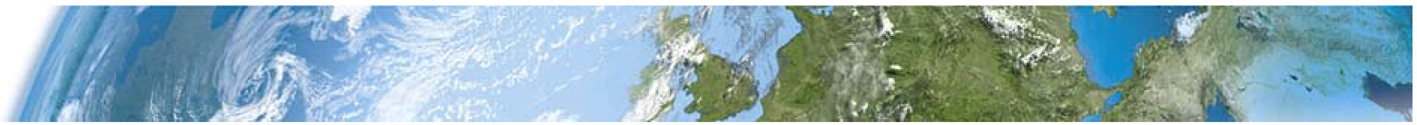
To demonstrate stand-alone, viable systems for the emission-free production of chemical fuels – especially **Hydrogen** - with sunlight



Highest efficiencies with concentrated sunlight?

Widest range of conditions?

Lowest cost?

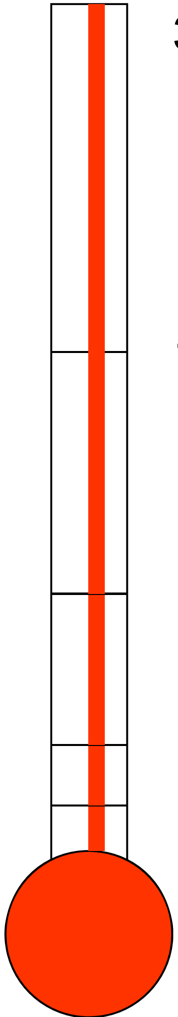


Efficiency comparison for solar hydrogen production from water (Siegel et al., 2013)*

Process	T [°C]	Solar plant	Solar-receiver + power [MW_{th}]	η T/C (HHV)	η Optical	η Receiver	η Annual Efficiency Solar – H_2
Elctrolysis (+solar-thermal power)	NA	Actual Solar tower	Molten Salt 700	30%	57%	83%	13%
High temperature steam electrolysis	850	Future Solar tower	Particle 700	45%	57%	76,2%	20%
Hybrid Sulfur-process	850	Future Solar tower	Particle 700	50%	57%	76%	22%
Hybrid Copper Chlorine-process	600	Future Solar tower	Molten Salt 700	44%	57%	83%	21%
Metaloxide two step Cycle	1800	Future Solar dish	Particle Reactor < 1	52%	77%	62%	25%

*N.P. Siegel, J.E. Miller, I. Ermanoski, R.B. Diver, E.B. Stechel, Ind. Eng.Chem. Res., 2013, 52, 3276-3286.

Temperature Levels of CSP Technologies



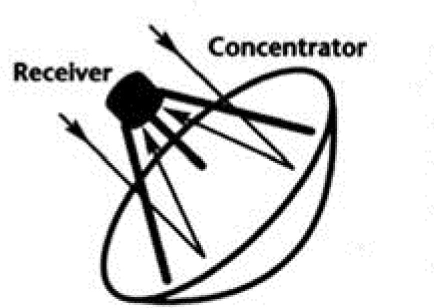
3500°C

1500°C

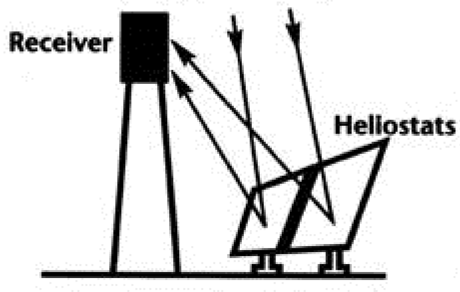
390°C

150°C

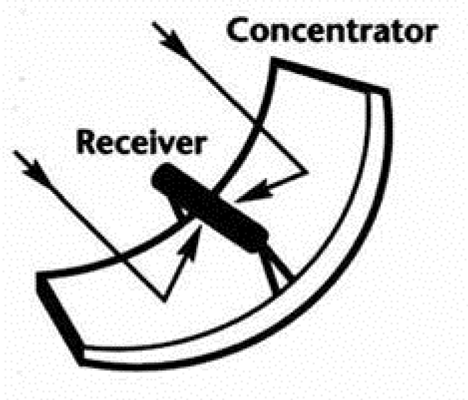
50°C



Paraboloid:
„Dish“



Solar Tower
(Central Receiver System)



Parabolic Trough /
Linear Fresnel

Solar Towers

http://www.ivanpahsolar.com/

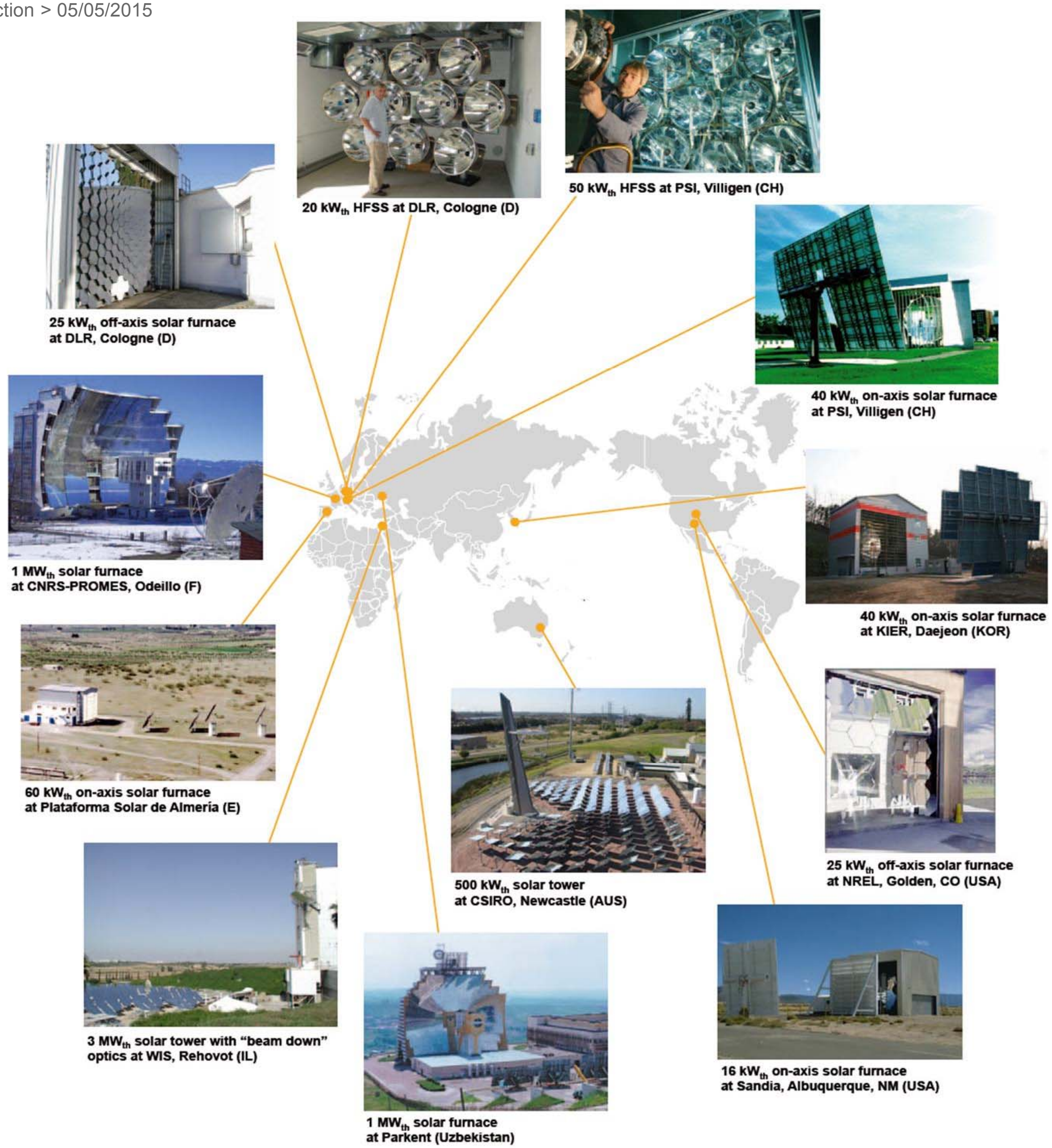
-PS10, Ivanpah, Torresol
-PSA CRS, CESA-1,
-Solar-Two, Daggett,

DLR

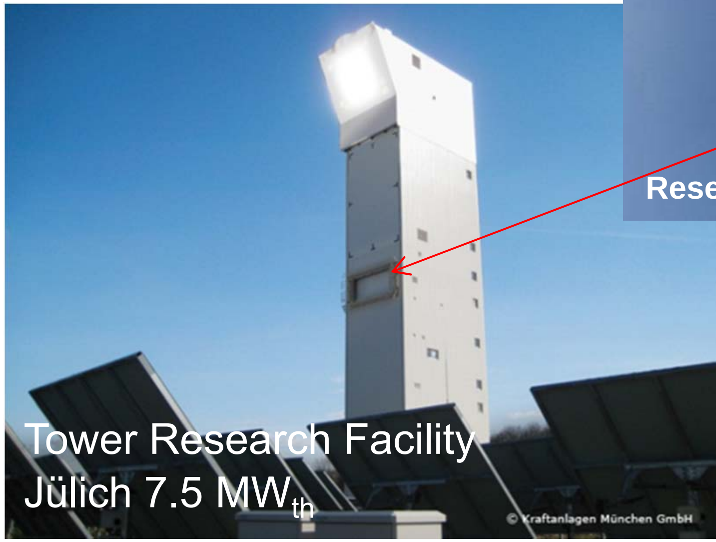
Solar Chemistry Research around the world

- Strong collaboration under the IEA “Solar Power and Chemical Energy Systems” (SolarPACES) program www.solarpaces.org

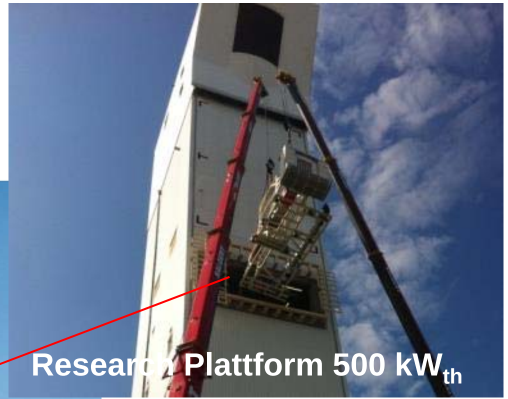
- New IEA-HIA Task 35 on renewable hydrogen production

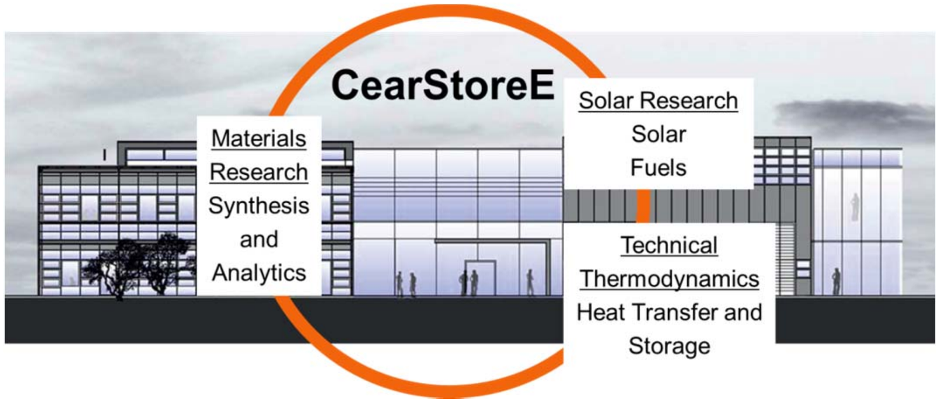


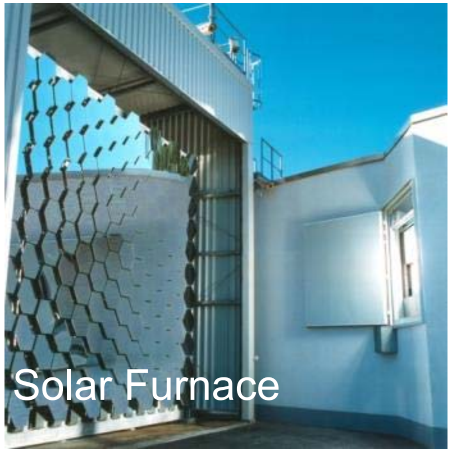
Large scale facilities used by DLR



Tower Research Facility Jülich 7.5 MW_{th}


Resear Plattform 500 kW_{th}

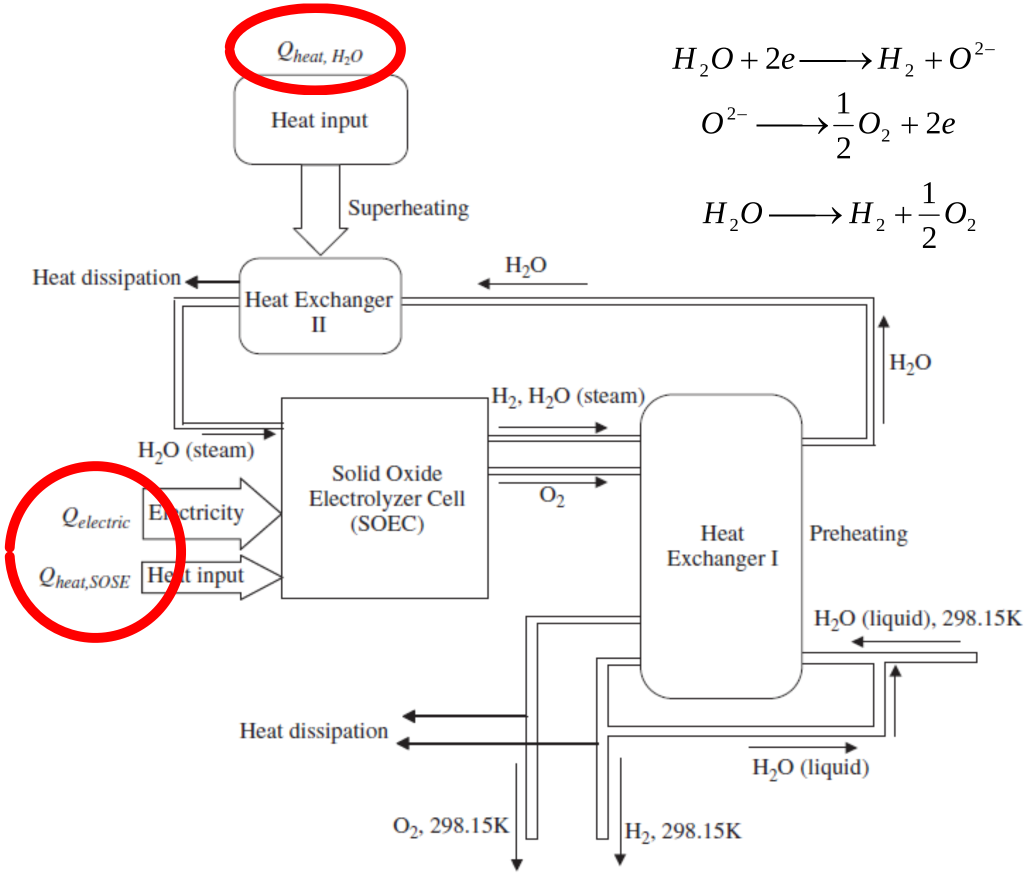



Solar Furnace


Solar Simulator

High temperature electrolysis process

- Temperature in the range of 600°C to 900°C are required to drive the electrolyser.
- Electricity and heat are supplied to the electrolyser to drive the electro-chemicals reactions.
- The waste heat from the H_2 and O_2 gas streams existing the cell is used to evaporate water.
- The H_2O stream is further heated by the second Heat exchanger to raise the temperature of the electrolyser.

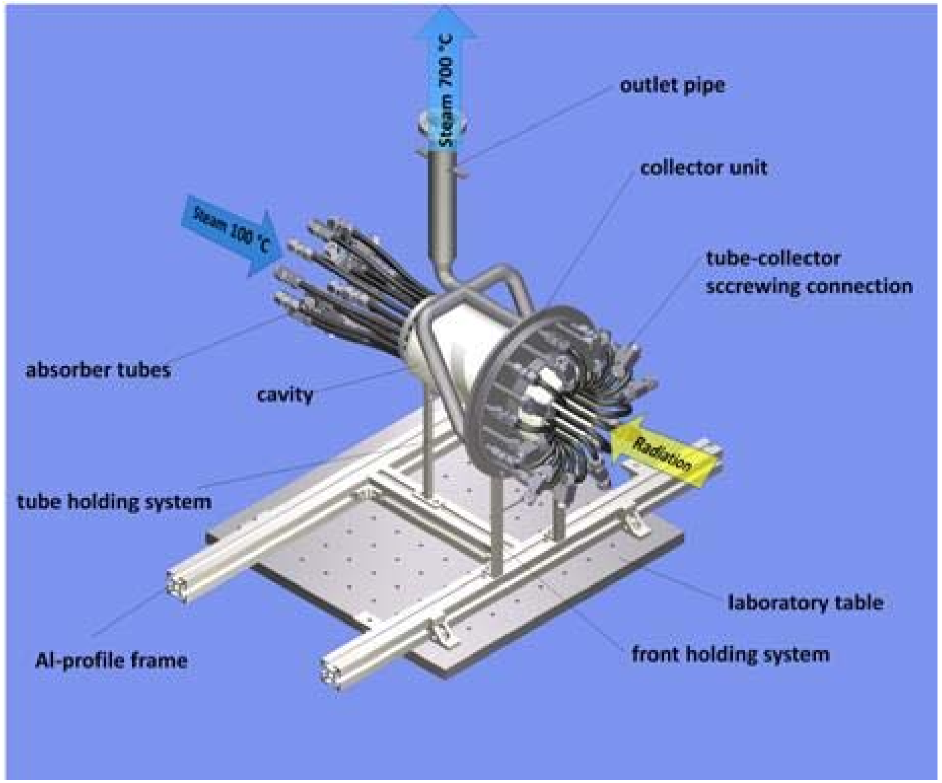


$$H_2O + 2e \longrightarrow H_2 + O^{2-}$$

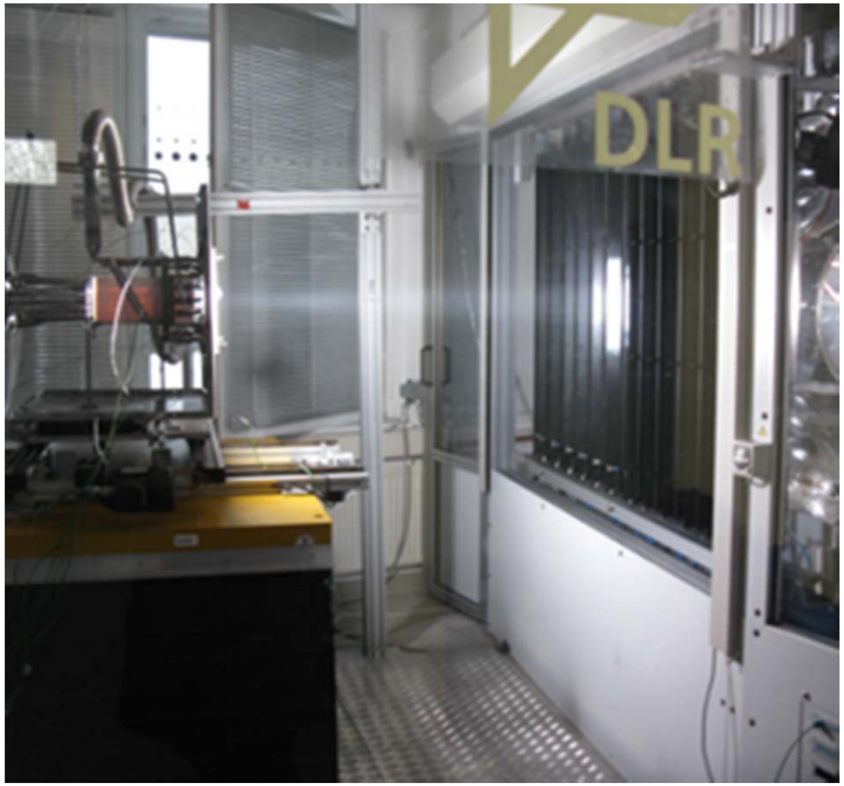
$$O^{2-} \longrightarrow \frac{1}{2}O_2 + 2e$$

$$H_2O \longrightarrow H_2 + \frac{1}{2}O_2$$

Solar Superheated Steam Generator for SOEC



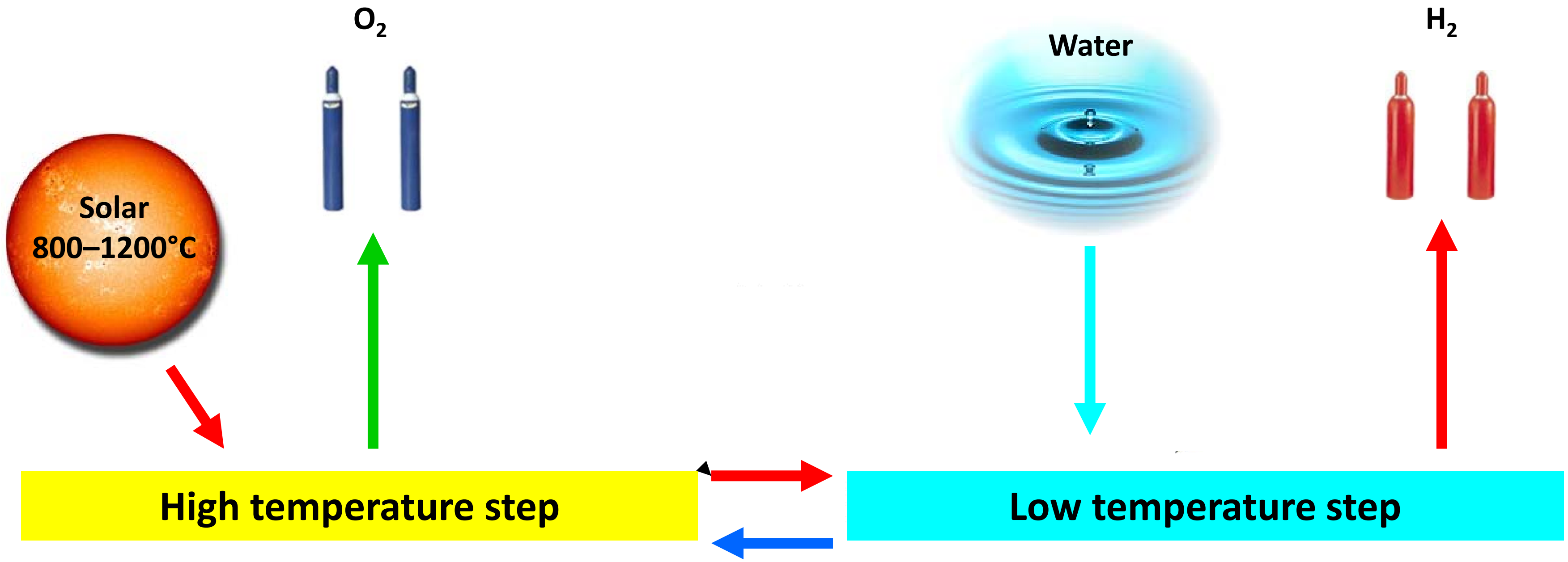
3D Design



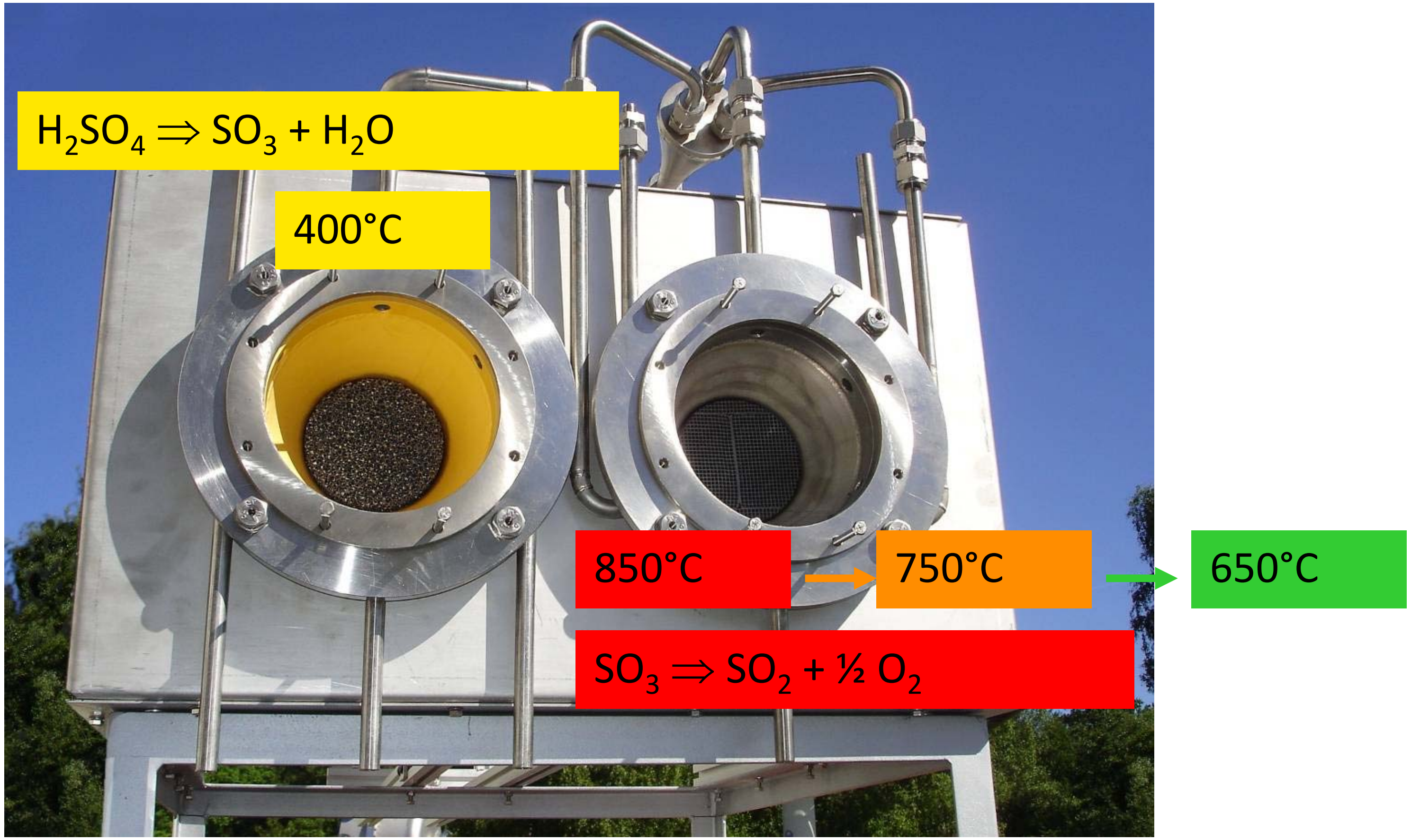
Operation in the solar simulator providing 5 kg/h steam at 700 °C

http://www.sophia-project.eu/

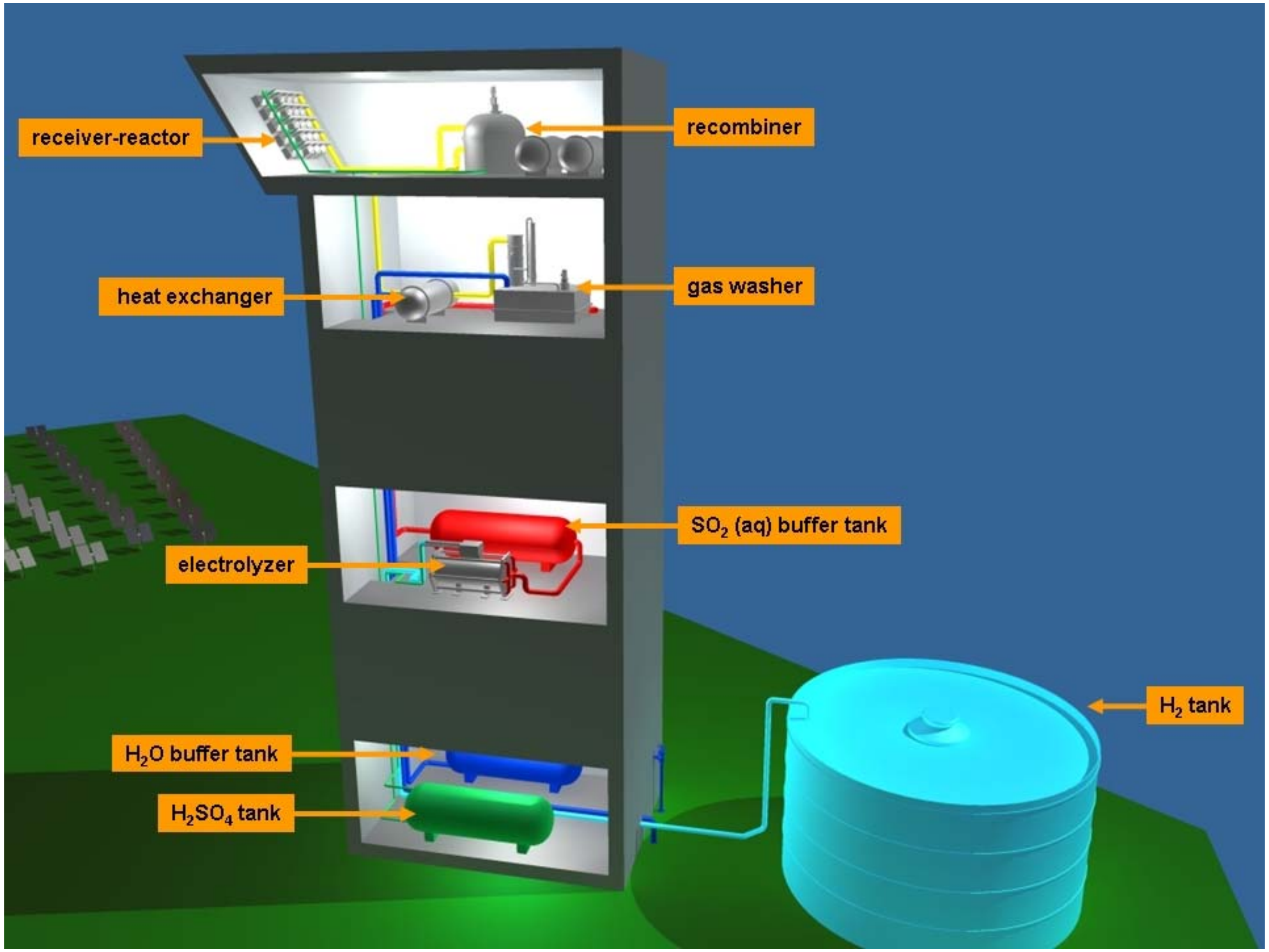
Hybrid Sulfur Cycle (HyS, Westinghouse)



Solar reactor for sulfuric acid decomposition



Implementation into a Solar Tower

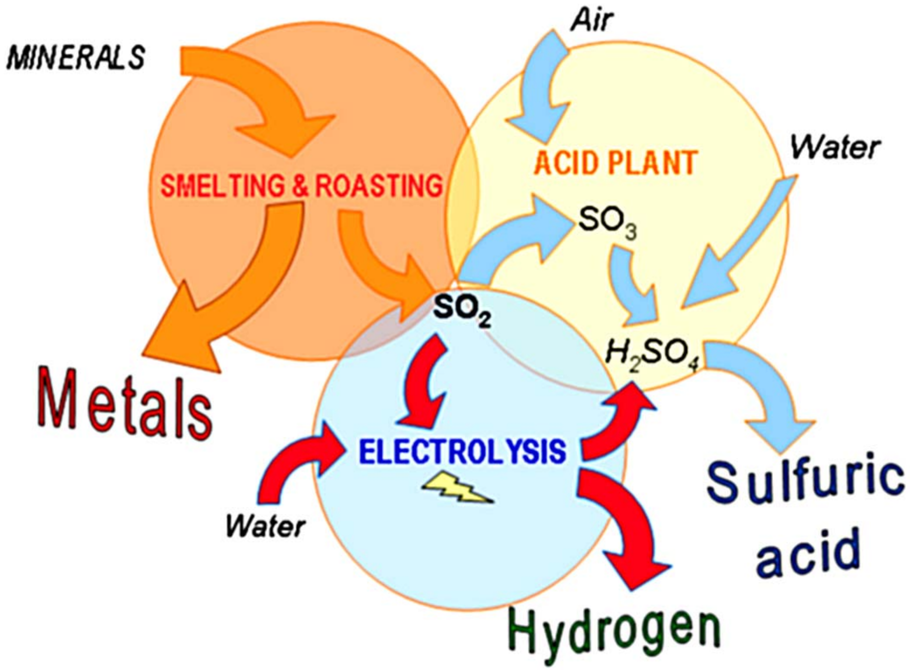


SOL2HY2 – Solar To Hydrogen Hybrid Cycles

- FCH JU project on the solar driven Utilization of waste SO_2 from fossil sources for co-production of hydrogen and sulphuric acid
- Hybridization by usage of renewable energy for electrolysis
- Partners: EngineSoft (IT), Aalto University (FI), DLR (DE), ENEA (IT), Outotec (FI), Erbicol (CH), Oy Woikoski (FI)
- >100 kW demonstration plant on the solar tower in Jülich, Germany in 2015

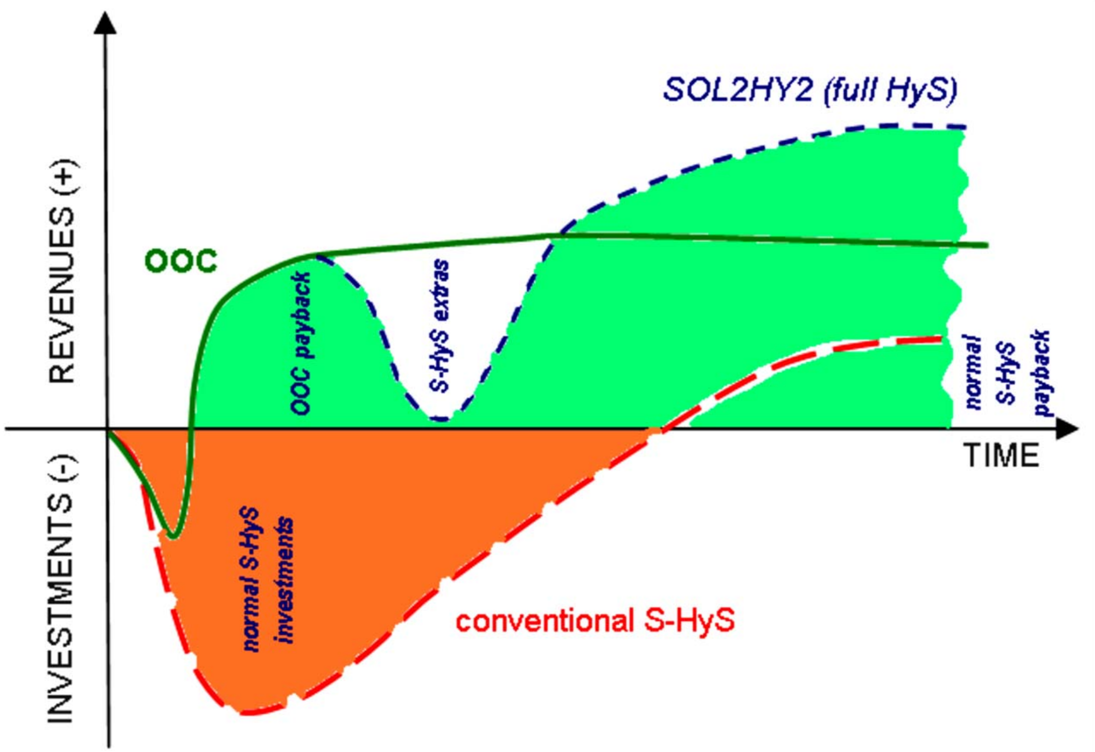
https://sol2hy2.eurocoord.com

Outotec[TM] Open Cycle (OOC)



- Utilization of waste SO_2 from fossil sources
- Co-production of hydrogen and sulphuric acid
- Hybridization by renewable energy for electrolysis

Investments vs. revenues



- Reduction of initial investments
- Financing of HyS development by payback of OOC
- Increase of total revenues

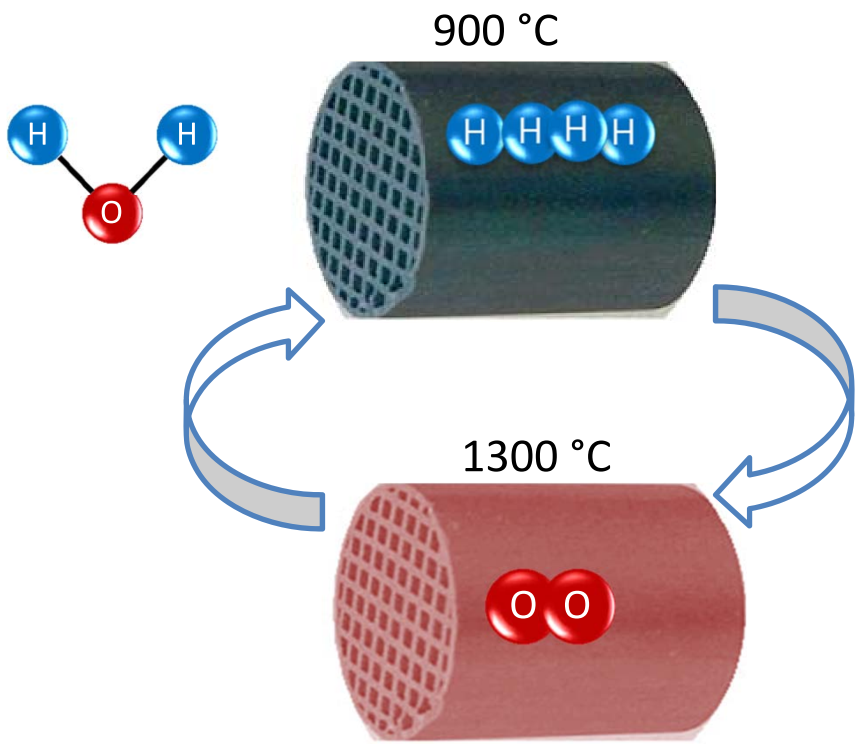
Example how a technology is developed The HYDROSOL concept

1. Water Splitting

$H_2O + MO_{red} \rightarrow MO_{ox} + H_2$

2. Regeneration

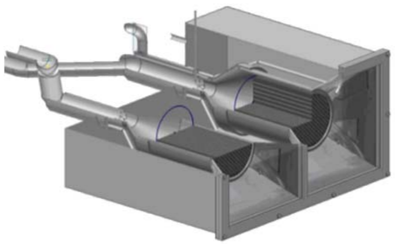
$MO_{ox} \rightarrow MO_{red} + ½ O_2$



Net Reaction: $H_2O \rightarrow H_2 + ½ O_2$

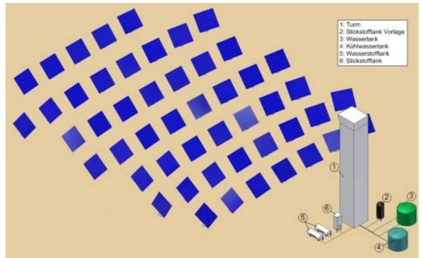
HYDROSOL Development

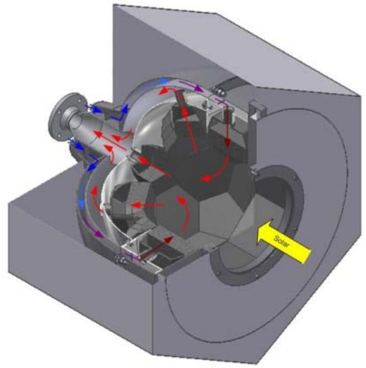
<u>Hydrosol I</u>
2002 – 2005
< 10 kW



<u>Hydrosol II</u>
2006 – 2009
100 kW

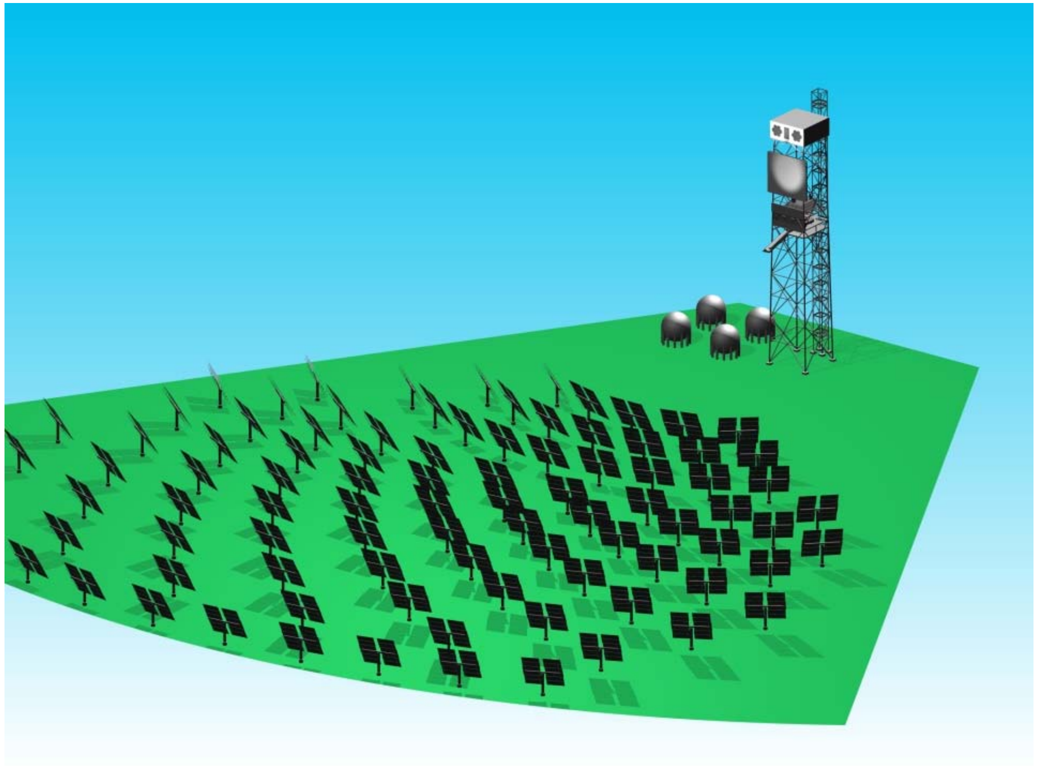
<u>Hydrosol 3D</u>
2010 – 2012
1 MW

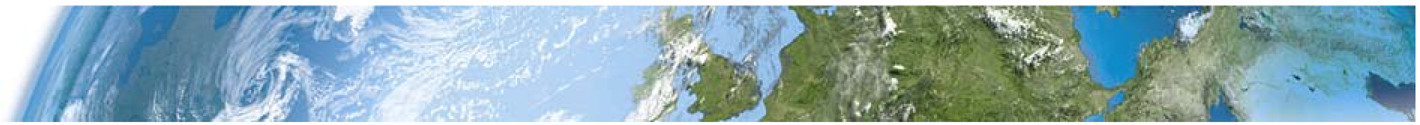




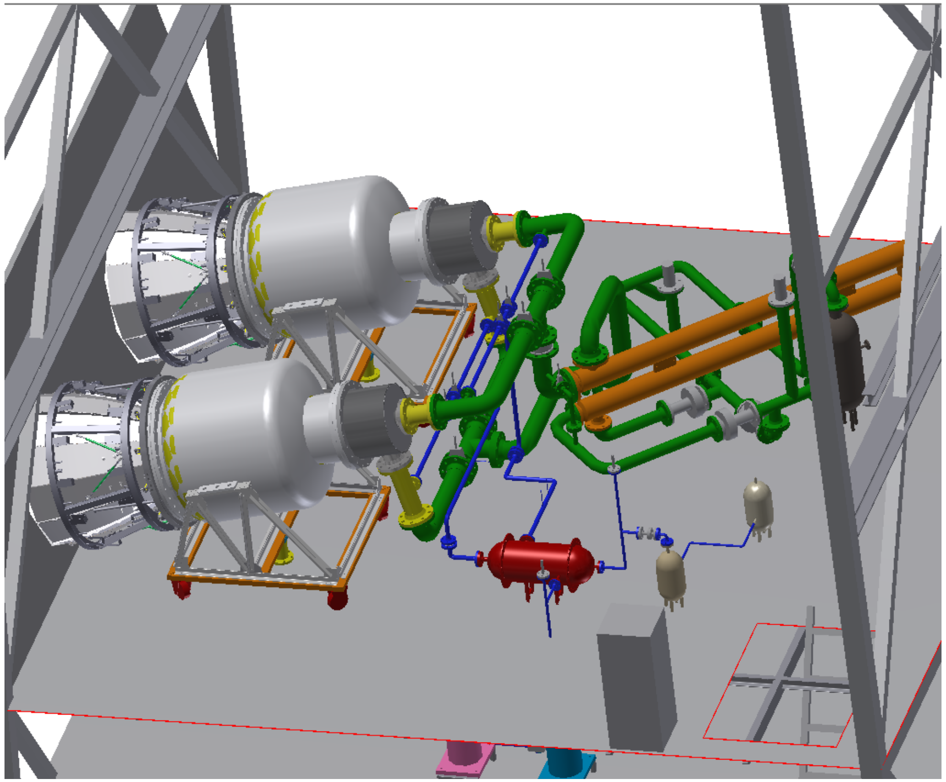
Hydrosol Plant - Design for CRS tower PSA, Spain

- European FCH-JU project
- Partner: APTL (GR), HELPE (GR), CIEMAT (ES), HYGEAR (NL)
- 750 kW_{th} demonstration of thermochemical water splitting
- Location: Plataforma Solar de Almería, Spain, 2016
- Use of all heliostats
- Reactor set-up on the CRS tower
- Storage tanks and PSA on the ground





HYDROSOL, HYDROSLOL 2, HYDROSOL-3D, HYDROSOL Plant



APTL (GR), DLR (DE), CIEMAT (SP), StobbeTech (DK), Johnson Matthey (UK), HyGear (NL), HELPE (GR)

- 2002 Start HYDROSOL, EU FP5
- 2004 First solar hydrogen, DLR
- 2005 Quasi-continuous solar hydrogen, DLR
- 2008 HYDROSOL 2, EU FP6, 100 kW demonstration CRS Tower PSA, Spain
- 2013 HYDROSOL-3D, FCH JU, Design of a 1,5 MW demonstration plant ready
- 2014 HYDROSOL PLANT, FCH JU
- 2016 Operation of the 750 kW Demonstration plant, CRS Tower, PSA, Spain

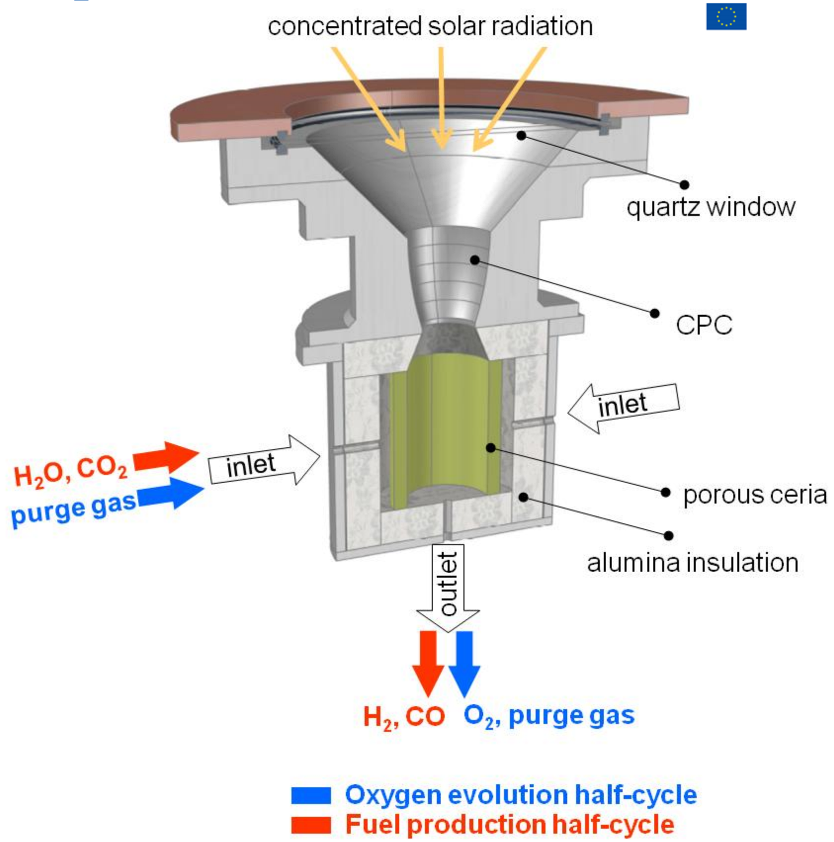
http://hydrosol-plant.certh.gr/

DLR

H_2O/CO_2-Splitting Thermochemical Cycles

Solar Production of Jet Fuel

- EU-FP7 Project SOLAR-JET (2011-2015)
- SOLAR-JET aims to ascertain the potential for producing jet fuel from concentrated sunlight, CO_2, and water.
- SOLAR-JET: optimize a two-step ceria based solar thermochemical cycle to produce synthesis gas (syngas) from CO_2 and water, achieving higher solar-to-fuel energy conversion efficiency over current bio and solar fuel processes.
- **First jet fuel produced in Fischer-Tropsch (FT) unit from solar-produced syngas**!



Int. J. Heat & Fluid Flow 29, 315-326, 2008.
Materials 5, 192-209, 2012.

Partners: Bauhaus Luftfahrt (D), ETH (CH), DLR (D), SHELL (NL), ARTTIC (F)
Funding: EC

http://www.solar-jet.aero/

Technical Optimization in all Dimensions necessary

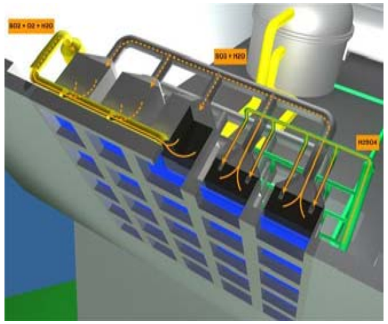
$10^4 - 10^2$ m
Solar Plant

Site

Solar field

Simulation

Environmental impact



$10^2 - 10^1$m
Receiver

Design

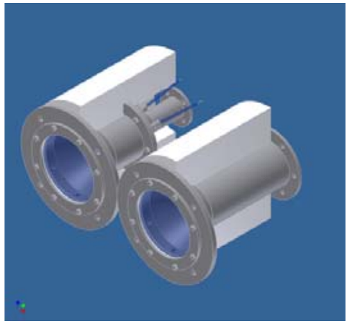
Simulation

Construction

Testing

Next-Generation-

Development



$10^1 - 10^{-2}$m
Receiver-components

Materials

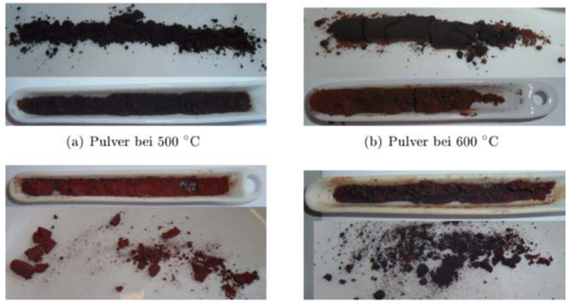
Design

Heat and

Mass transport

Simulation

Testing and Develpment



(a) Pulver bei 500 °C (b) Pulver bei 600 °C (c) Pulver bei 800 °C (d) Pulver bei 900 °C

$10^{-2} - 10^{-8}$ m
Reactive Systems

Simulation

Synthesis

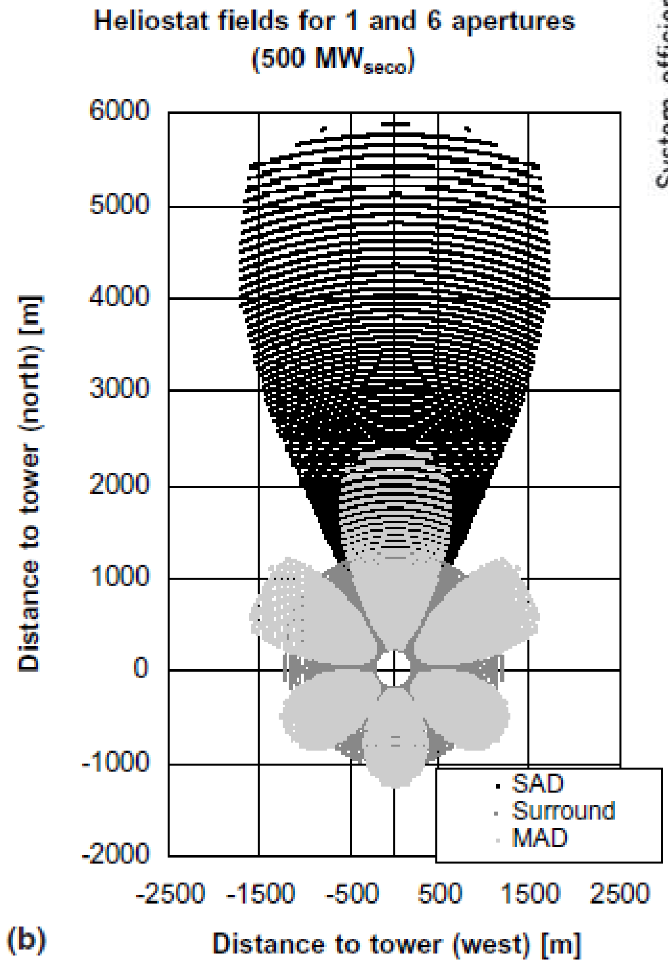
Chemical Charactristics

Physical Characteristics

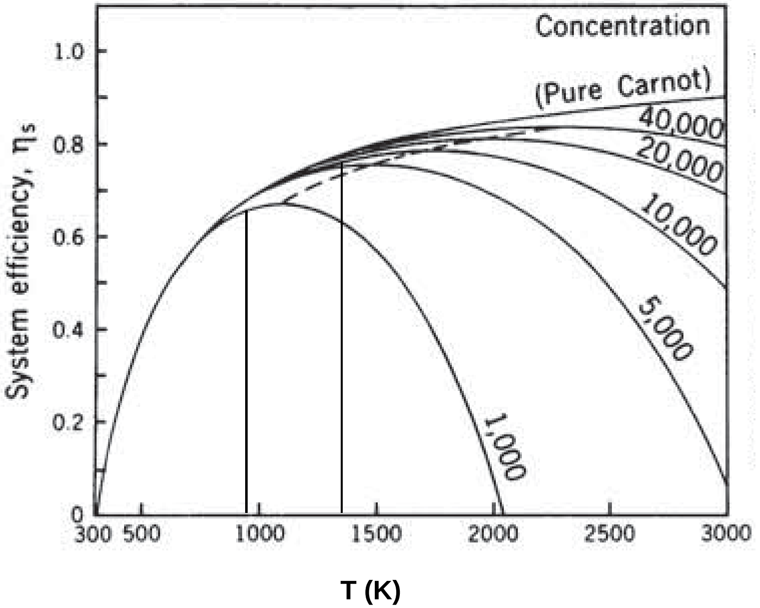
Solar Field Development

The field has to be designed for its application:

- Location
- Concentration ratio to achieve the Process temperature
- At high concentration (1000 suns) secondary optics have to be taken into account



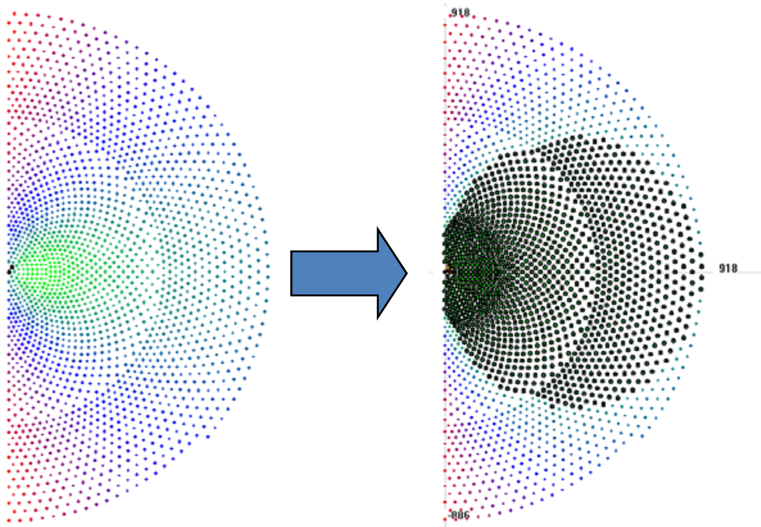
M. Schmitz et al., Solar Energy 80 (2006) 111–120.



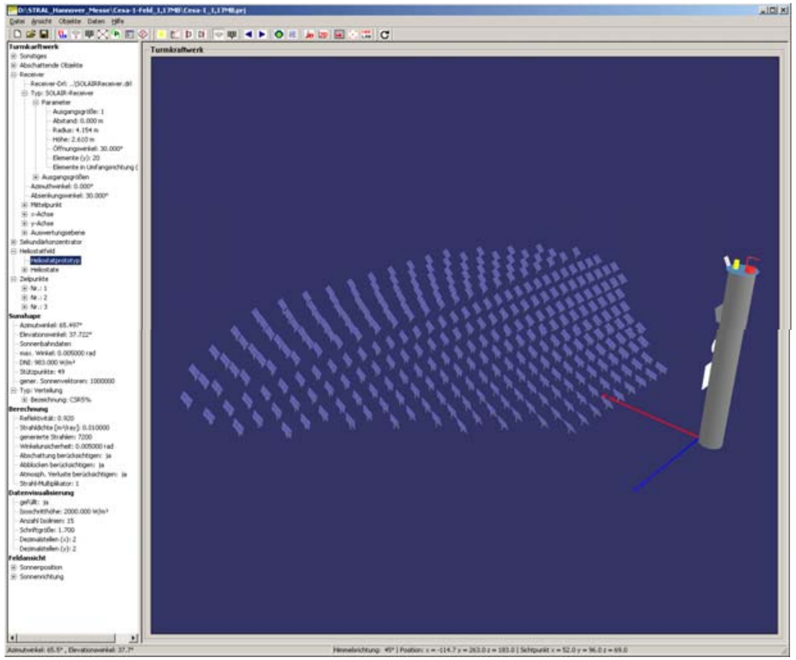
E.A. Fletcher, R.L. Moen, Science, 197 (1977) 1050-1056.

Simulation Tool Development
for Solar Tower Systems

- Heliostat field layout



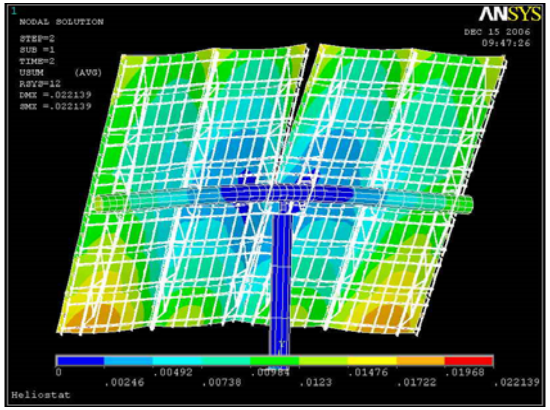
- Performance simulation
    - flux distribution
    - aim point strategy
    - efficiency

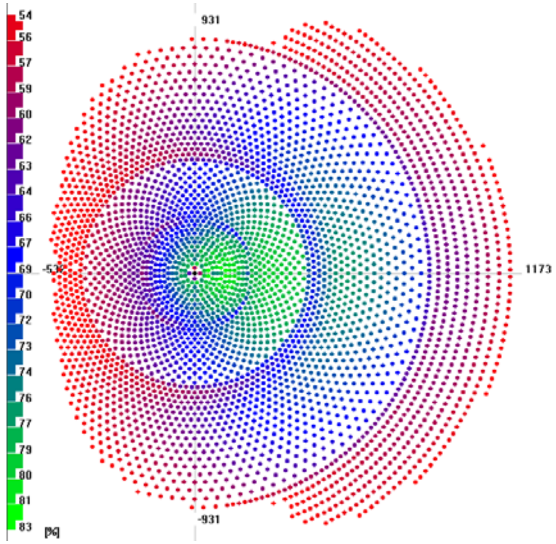


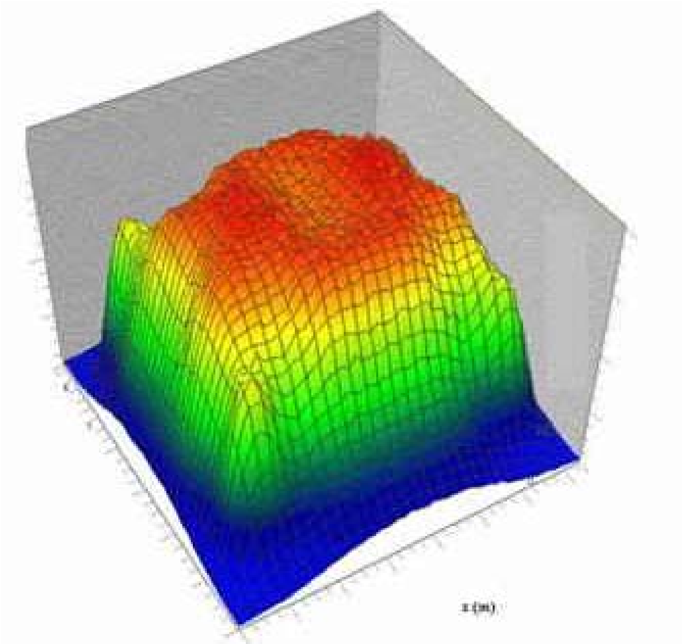
DLR

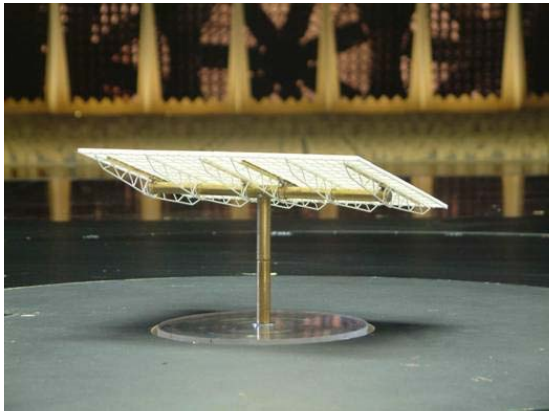
Heliostat R&D

- Heliostat and field simulation
- Structural analysis
- Load analysis
- Qualification
- Control
- Operation strategy

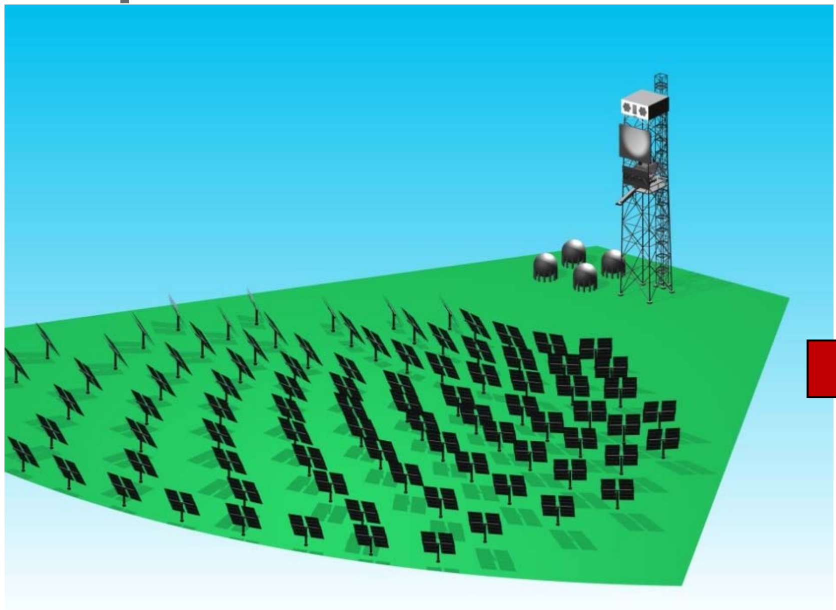




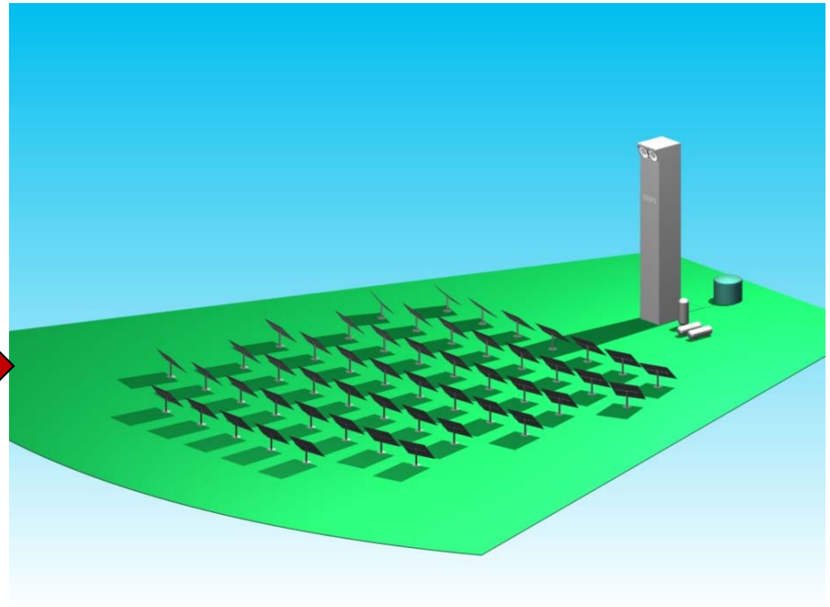




Next Step:
Specific Solar Fuel Demonstration Tower needed!



CRS Tower PSA, Spain
2008 and 2016

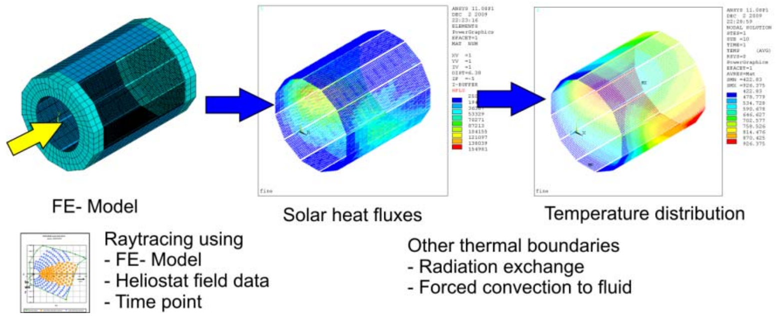


Solar Fuels Tower, Location?
2020

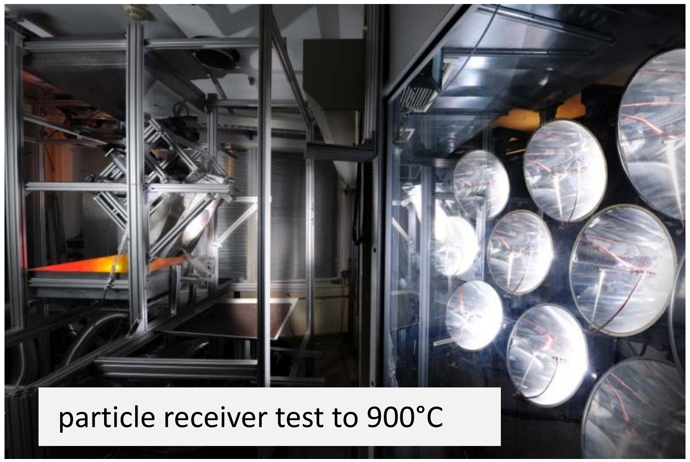
- High concentration > 1000
- Heliostats fit to receiver size
- Field control adapted to fuel production processes

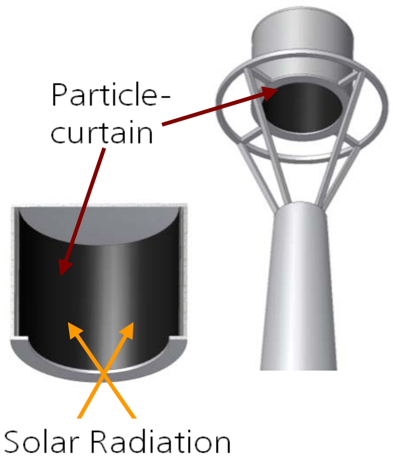
Receiver Technology R&D

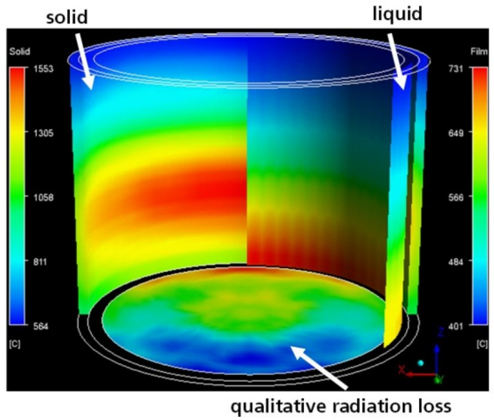
- Development / technology transfer
  - open volumetric air receivers
  - pressurized air receivers



- Extension to liquid heat transfer media
  - e. g. molten salt
- Innovative concepts: direct absorption receivers



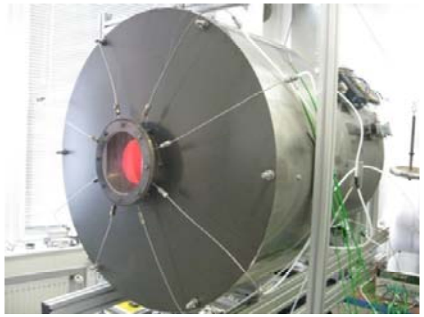


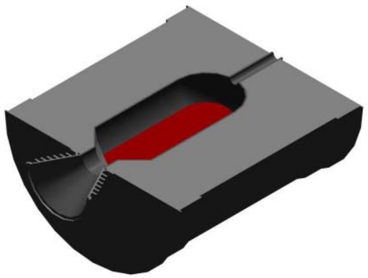


Receiver – Concepts for Solar Chemistry

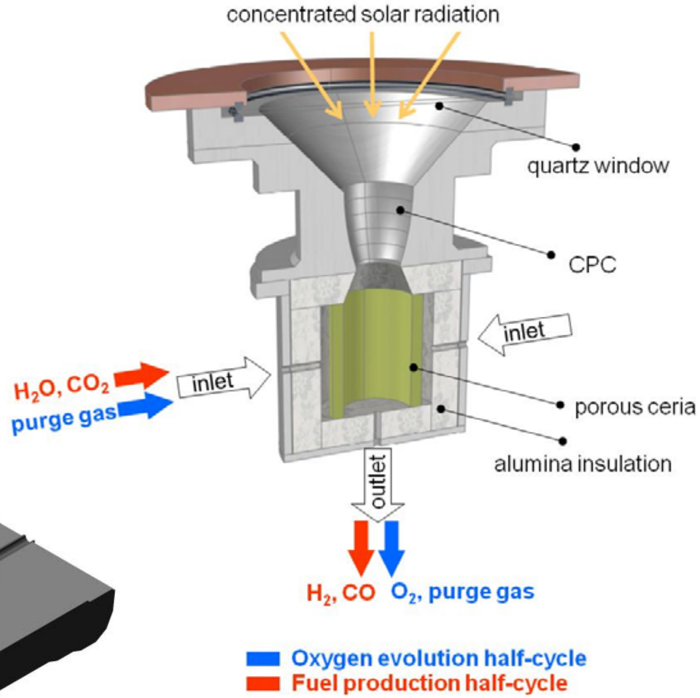
- Challenges:
  - Temperature
  - Corrosion
  - Abrasion
  - Process operation

- Goals:
  - Efficiency
  - Durability
  - Cost

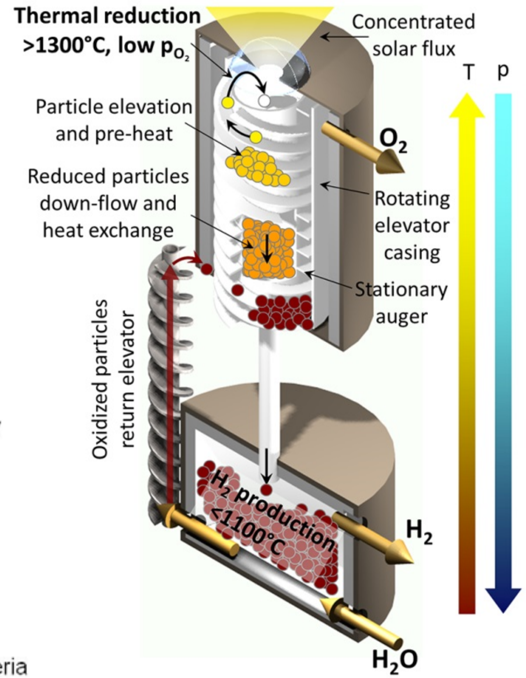


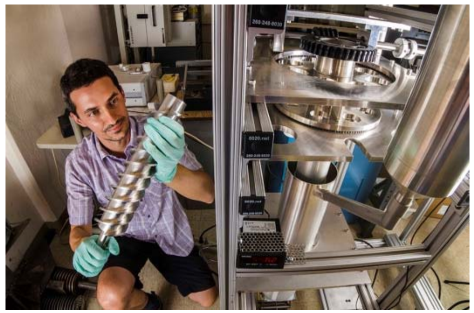


German Project
Solar heated rotary kiln, DLR



European Project
Solar heated Cavity-Gas Receiver
with porous Ceramic structur
A. Steinfeld et al., ETH Zürich





DoE Project with DLR participation
Solar heated Particle-Receiver
I. Ermanoski et al., Sandia Natl. Lab.

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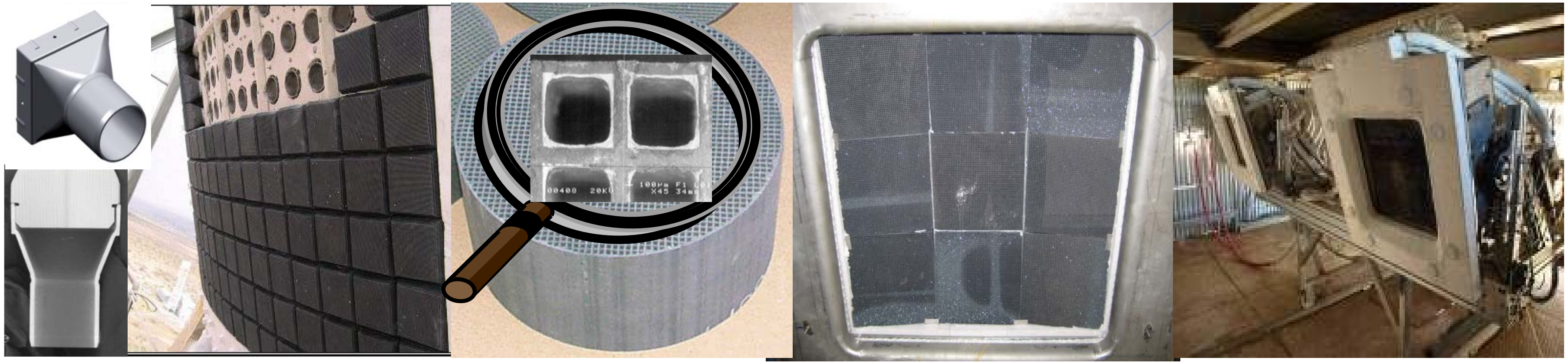
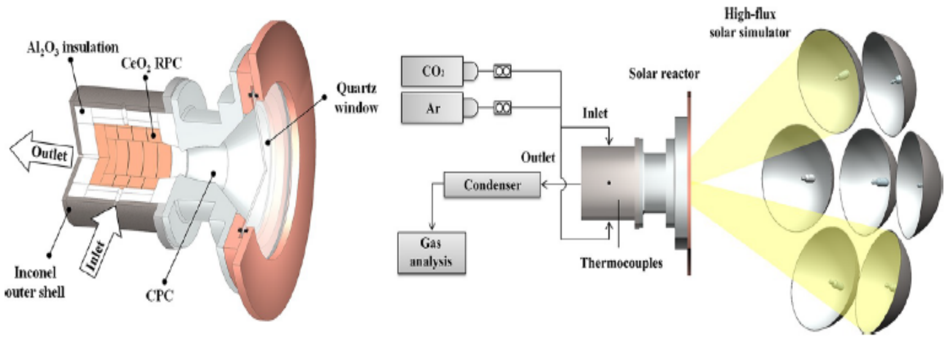
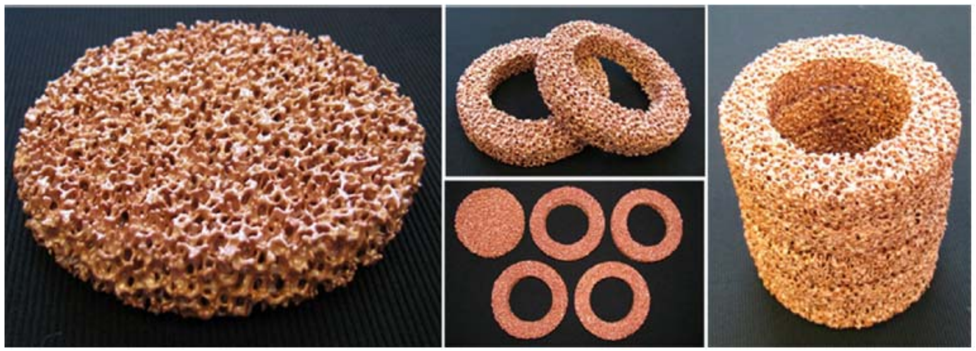
Solar Receiver Components and reactive Systems



C. Agrafiotis, M. Roeb, A.G. Konstandopoulos, L. Nalbandian, V.T. Zaspalis, C. Sattler, P. Stobbe, A.M. Steele, Solar water splitting for hydrogen production with monolithic reactor, Solar Energy, 79(4), 409-421, (2005).

Reactive coated structures and structures made from reactive materials





P. Furler, J. Scheffe, M.Gorbar, L. Moes, U. Vogt, A. Steinfeld, Solar Thermochemical CO_2 Splitting Utilizing a Reticulated Porous Ceria Redox System, Energy & Fuels, 26(11), 7051-59, (2012).

Overview of DLR CSP simulation tools

- DLR simulation tools cover all levels of CSP simulation

GREENIUS: analysis of performance / economics of renewable energy systems

ebsSolar®: detailed performance analysis of CSP systems

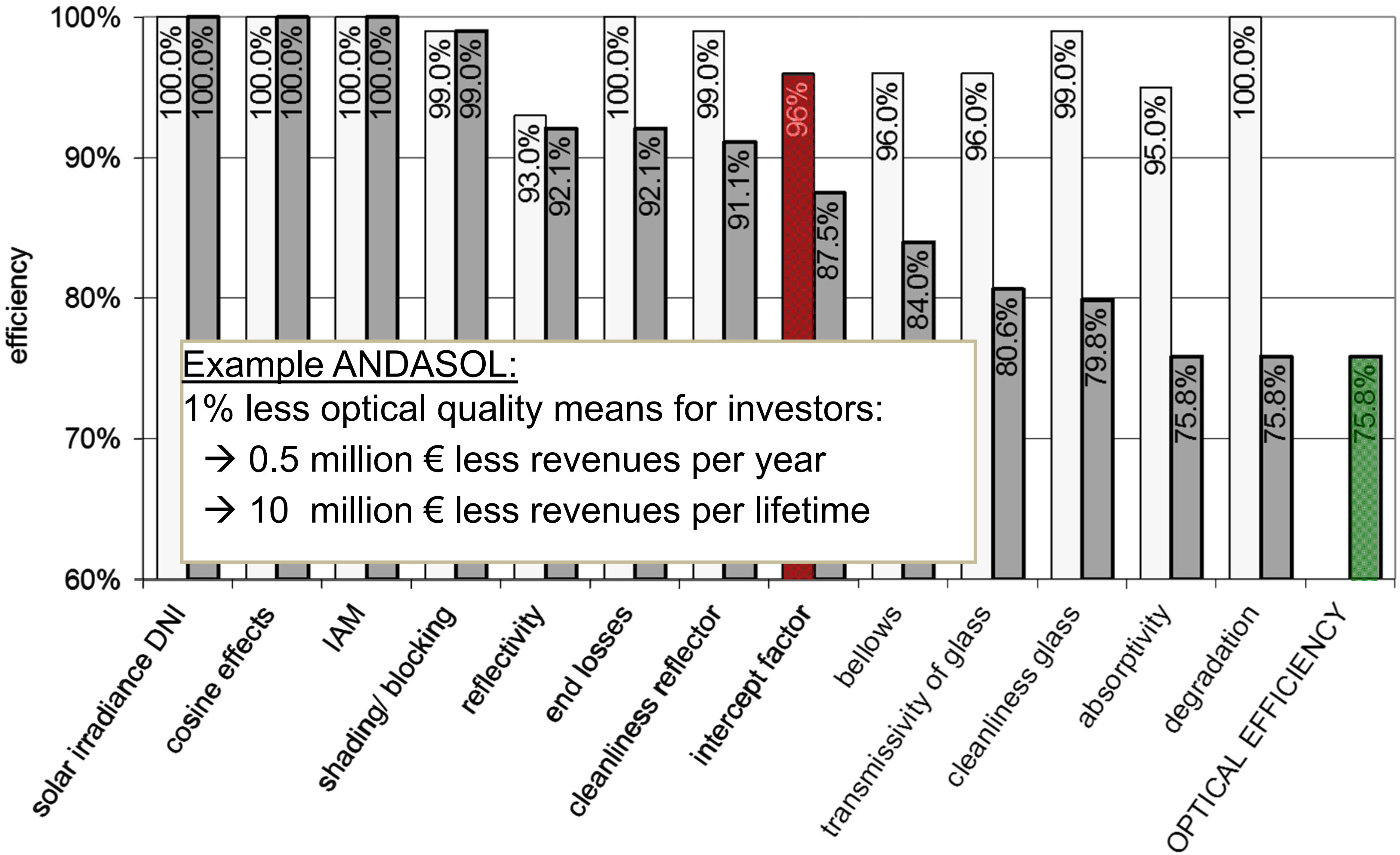
component layout:
- concentrators (parabolic trough, Fresnel, heliostats)
- receivers

system layout optimization:
- solar field, receiver
- power block
- storage

transient system simulation:
- real-time, high resolution performance simulation
- coupling of components and control

Qualification - Motivation

Efficiency Chain, Example: Parabolic Trough



<u>Example ANDASOL:</u>

1% less optical quality means for investors:

→ 0.5 million € less revenues per year

→ 10 million € less revenues per lifetime

QUARZ® – Center
Test and Qualification Center for CSP Technologies

- Strong impact on the **performance and cost efficiency**:
  - CSP component quality and durability
  - their interaction in the overall system
  - and the meteorological conditions each

- Development of **measurement techniques and devices**
- Evolution of **guidelines and standards**
  - testing methods
  - quality criteria

- Customer oriented services
  → Fundamental information for industry to
    - **Improve** quality, performance → **competiveness**
    - **Proof** of product quality → successful **market entry / bankability**

  → Consulting and training

EERA – European Energy Research Alliance

EERA supports the EU SET-Plan by accelerating the development of energy technologies through joint R&D

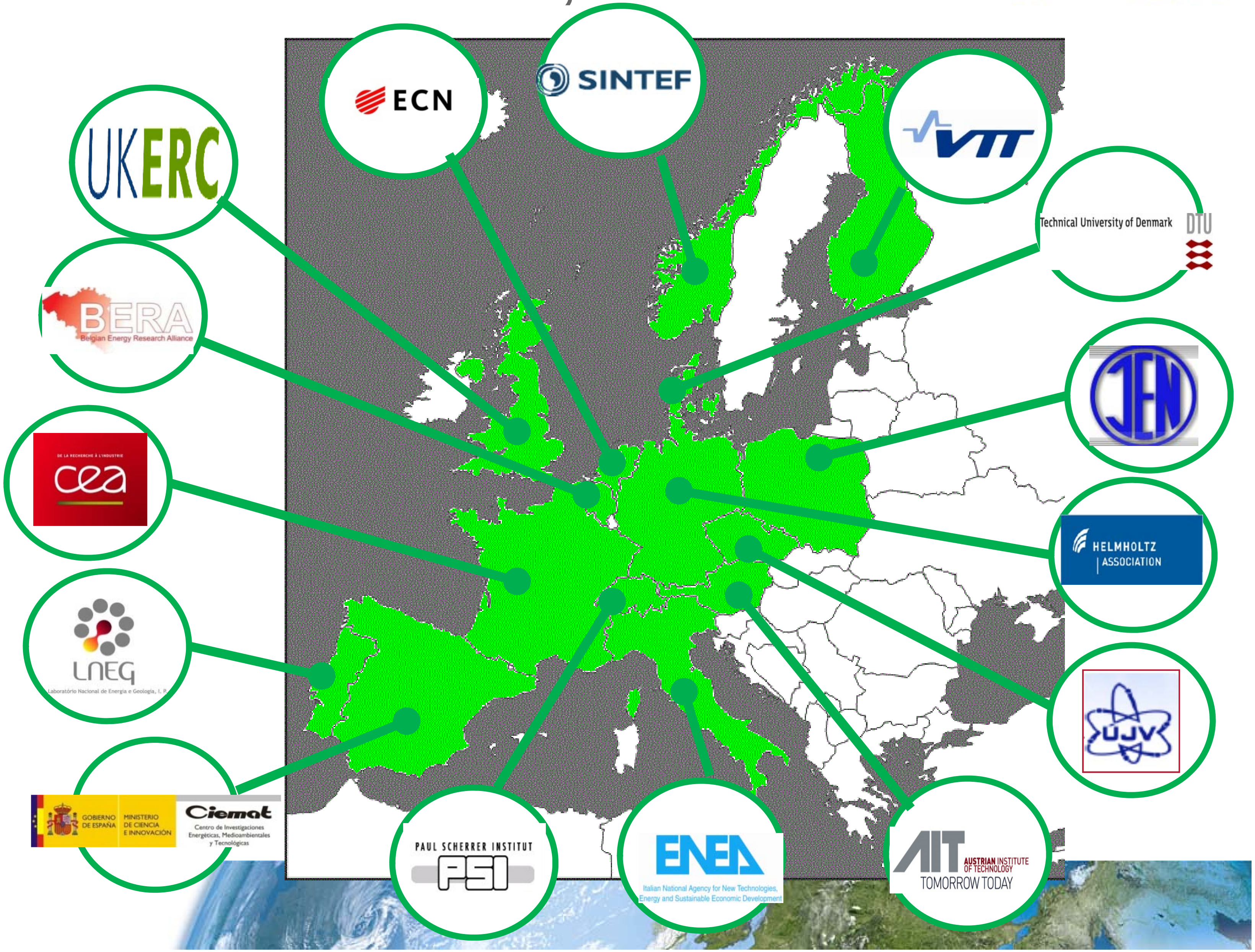
EERA reinforces Europe’s role by supporting the competitiveness of industry at international level.

The relevance of research will be enhanced in close cooperation with Member States, the EC and industry to support the political and industrial SET-PLAN objectives.

EERA – Executive Members, 2012 - 2014

Supported by :

EUA European University Association



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EERA – Joint Programmes (JPs)

Overall 15 EERA
Joint Programmes

Joint Programmes launched 2010

- Bioenergy
- CCS
- Geothermal
- Mat. for Nuclear
- PV
- Smart Grids
- Wind

Joint Programmes launched 2011

- AMPEA (Materials & Processes)
- **CSP**
- Energy Storage
- **Full Cells & Hydrogen**
- Ocean Energy
- Smart Cities

Joint Programmes launched 2013

- JP on socio economic impact
- Shale Gas

FP7 – Integrated Research Programmes (IRP)

Funding	Proposal	Topic
Yes	STAGE-STE	CSP
Yes	ELECTRA	Smart Grids
Yes	IRPWIND	Wind
Yes	CHEETAH	PV
No	BIOENERGY IRP	Bio-energy
No	EESTORIGA	Energy Storage

EERA will:

- Coordinate common set of KPIs
- Evaluate the different mobility schemes
- Compare situation of national programmes
- Identify common elements of IRP consortium agreements
- …

→ for preparing future EERA IRPs or European Co-Fund Actions

STAGE-STE Consortium (today)

www.stage-ste.eu

Organisation name	Country
CIEMAT	SPAIN
DLR	GERMANY
PSI	SWITZERLAND
CNRS	FRANCE
FISE	GERMANY
ENEA	ITALY
ETHZ	SWITZERLAND
CEA	FRANCE
CYI	CYPRUS
LNEG	PORTUGAL
CTAER	SPAIN
CNR	ITALY
CENER	SPAIN
TECN	SPAIN
UEVORA	PORTUGAL
IMDEA	SPAIN
CRAN	UK
TKN	SPAIN
UNIPA	ITALY
CRS4	ITALY

Organisation name	Country
INESC-ID	PORTUGAL
IST-ID	PORTUGAL
SENER	SPAIN
HITIT	TURKEY
ACCIONA	SPAIN
SCHOTT	GERMANY
ASE	ITALY
ESTELA	BELGIUM
ABENGOA Solar	SPAIN
ASNT	SPAIN
KSU	SAUDI ARABIA
UNAM	MEXICO
SUN	SOUTH AFRICA
CSERS	LYBIA
CSIRO	AUSTRALIA
FUSP	BRAZIL
IEECAS	CHINA
UDC	CHILE
UCAM	MOROCCO
FBK	ITALY

Summary and Outlook

- Hydrogen will play a **key role** in reducing CO_2 emissions
- **Synergies** between hydrogen production technologies should be used to
  - Accelerate **development and deployment**
  - Raise the **acceptence** for hydrogen in the society
  - **Support industry** to be successful with innovative technologies
- Solar thermochemical processes have a high potential to be efficient renewable pathways for **large scale hydrogen production**
- Technologies are **demonstrated** in the > 100 kW_{th} range
- Further **developments and demonstrations** are necessary to achieve a **market introduction**

  - Acknowledgement: Thanks to everyone who contribute to the development of sustauinable hydrogen production, especially the European Commission for funding projects within the FCH-JU and the RFPs

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OBJECTS IN MIRROR ARE CLOSER
THAN THEY APPEAR
DLR
Thank you very much for your attention!